REDUCING RISKS DUE TO ROCKBURSTS: STRATEGIC FINANCIAL CONSIDERATIONS

Kadibetjo Adelaide Moganedi

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DECLARATION

I declare that this dissertation is my own unaided work. It is being submitted for the Degree of Master of Science in Engineering to the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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ABSTRACT

Gold mines in the Far West Witwatersrand area experience frequent mining induced seismic events due to dynamic stress changes associated with the depth and extent of mining. Some of these seismic events result in rockbursts, of varying magnitudes, in access tunnels. Geological structures, mine design layout and support system design influence the magnitude of a rockburst damage in an underground excavation. Support systems are the last line of defence and are effective in environments where the mining layout is optimised for dynamic stress changes.

The objective of this research is to determine the financial value energy absorbing support systems add to a rockburst prone well designed mine. The research focuses on quantifying indirect consequences of rockburst risk using an Excel model developed as part of this research. The model has three versions, each targeting a specific user. The model is used to evaluate the financial benefits of different support systems in access tunnels prone to seismicity and possible rockbursts. Executive management can use the Executive spreadsheet of the model to facilitate proactive rockburst risk management.

Four case studies were evaluated in detail, and the results indicate production loss is the major source of quantifiable financial loss after a rockburst. The tunnels were supported with variations of rigid support systems, even though energy-absorbing support systems were the most suitable for dynamic loading conditions, and were likely to have contained the rockburst events. This is because energy-absorbing support systems are viewed as an unnecessary expense. However, the “extra” cost of energy absorbing support system, as a strategy to minimise effects of rockbursts, will almost always create better value than the less expensive rigid support. This extra cost can be significantly reduced by increasing the spacing between yielding tendons in an energy absorbing support system. In conclusion, it is strategic for rockburst prone mines to install high quality yielding support systems as they have the potential to create substantial long term value for the mine.

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NOMENCLATURE

Acceptable risk:	The residual risk remaining after controls have been applied to associated hazards that have been identified, quantified to the maximum extent practicable, analysed, communicated to the proper level of management and accepted after proper evaluation.
Consequence:	The outcome of an event expressed qualitatively or quantitatively, being a loss, injury, disadvantage or gain. There may be a range of possible outcomes associated with an event.
Cost:	Of activities, both direct and indirect, involving any negative impact, including money, time, labour, disruption, goodwill, political and intangible losses.
DMR:	Department of Mineral Resources, is a department of the national government of South Africa which is responsible for overseeing the mining industry of South Africa and the exploitation of the country's mineral resource
Frequency:	A measure of the rate of occurrence of an event expressed as the number of occurrences of an event in a given time.
Hazard:	A potential occurrence or condition that could lead to injury, damage to property, delay or economic loss.
Risk assessment:	The overall process of risk identification, risk analysis and evaluation.
Risk identification:	The process of determining what can happen, why and how.

Risk analysis: A structured process that identifies both the likelihood and the consequences of hazards arising from a given activity or facility.

Risk evaluation: Involves the comparison of the results of a risk analysis with risk acceptance criteria or other decisions. If the risk does not meet the risk criteria, the risk is treated, that particular risky option discarded, or risk control options sought.

Risk acceptance: An informed decision to accept the consequences and the likelihood of a particular risk.

Risk management: The process by which decisions are made to accept known risks, or to implement actions to reduce unacceptable risks to acceptable risk levels.

Rockburst: Violent ejection of rock material off the periphery of excavations.

Seismicity: Unstable energy redistribution caused by dynamic energy changes often associated with slip or rock material failure.

Value: The worth of something compared to the money paid for it.

1 CHAPTER 1: INTRODUCTION

1.1 Research Background

The South African gold mining sector is facing challenges due to a greater number of mining-induced seismic events and the resulting rockbursts. The damage associated with a seismic event is called a rockburst. Stacey (2011) and Brady & Brown (2006) define a rockburst as dynamic failure of rock mass due to unstable energy changes in the rock mass. The dynamic rock failure is characterised by violent ejection of rock mass from the periphery of excavations.

A rockburst is a threat to the safety of personnel and to the financial performance of a mine. It is a hazard, i.e. a potential source of harm while a rockburst risk is a function of the probability of experiencing a rockburst and the magnitude of the consequences of the rockburst. The consequences discussed in this dissertation are limited to the indirect quantifiable financial consequences of the rockbursts, as money motivates change. The quantified consequences can help indicate the magnitude of the potential rockburst risk. Rockburst risk has to be minimised, as it cannot be eliminated unless mining ceases. Therefore, a long-term strategy to minimise rockburst risk is to install energy-absorbing support systems in a well-designed mining layout.

At great depths, the prevalence of seismicity and rockbursts is greater due to the depth and extent of mining. Deep level gold mining is largely conventional and labour intensive. Therefore, rockburst risk is high, owing to a greater probability of experiencing a rockburst and the large number of exposed personnel. Rockburst risk negatively affects financial performance of a mine and relationship with stakeholders. Negative stakeholder relations may result in industrial actions, stringent laws and loss of investor confidence, among other things.

1.2 Problem Statement

The mining industry is facing financial challenges and diminishing accessible gold reserves, which result in increasing costs. This brings the necessity to improve or preserve the financial performance of an operation, which often leads to cost cutting measures during support installation thus compromising the effectiveness of a given support system. A comprehensive energy absorbing support system is considered an expensive luxury, dubbed “The Rolls-Royce” of support. Common practice is to erroneously use basic rigid support units in an environment subjected to dynamic loading in an attempt to minimise costs. The act of minimising costs by installing unsuitable support is nullified by the consequential financial loss experienced after a rockburst event. The financial consequences of a rockburst often far outweigh the perceived cost benefits of the less expensive rigid support system.

An energy absorbing support system may appear to be expensive during installation, but its benefits will outweigh that of rigid support should a rockburst event occur. In an effort to encourage diligent implementation of energy absorbing support systems, an Excel model has been developed to help evaluate how much financial value energy absorbing support systems can preserve or add to a rockburst prone deep level gold mine.

1.3 Research Objectives

The main aim of the research is to evaluate the financial benefits of energy absorbing support systems in rockburst-prone deep level gold mines. The primary objective is to develop a model to estimate the financial value created by different support systems; by comparing financial losses incurred during a rockburst and costs of different support systems. This will be achieved by attaining the following objectives:

- Collecting data of different access tunnel rockburst case studies at two mines and quantifying the consequences of these rockbursts;
- Identifying alternative energy absorbing support systems that could have been appropriate for these access tunnels and quantifying their costs;
- Developing an Excel model to evaluate the value added by alternative support systems.

1.4 Research Methodology

The research is primarily a quantitative study. To collect the required data, seven weeks were spent at two deep level Far West Witwatersrand (Rand) gold mines and the following were achieved:

- A catalogue of the mines' rockburst related reports describing rockburst events in access tunnels was compiled. The catalogue has information such as the type of rockburst, the support that was installed and the recommended support;
- Costs associated with rockbursts were obtained from the Finance Department. These costs included labour, support material costs and medical costs;
- Underground visits were carried out to observe installed support in access tunnels;
- Time was spent with the site Rock Engineering Department to understand the geotechnical processes behind mine layout planning (siting of access tunnels) and support design and installation practices.

1.5 Dissertation Structure

The dissertation is presented in six chapters listed below:

Chapter 1: an introductory chapter of the research topic.

Chapter 2: a literature study on seismicity and rockburst activity in mining, the concept of risk in mining terms, rockburst as a risk, financial consequences and management of rockburst risk. Chapter 2 deals with strategies for mitigating rockburst risks in mining.

Chapter 3 describes the formulation of the Excel model. It explains how to interact with the interface of the model and describes the formulae used in the model.

Chapter 4: the Excel model is applied to the rockburst case studies to determine the value created by different support systems. Results obtained are discussed and analysed.

Chapter 5: is a discussion of the roles of the Excel model and rockburst risk in underground support design.

Chapter 6: conclusions are drawn regarding the value of energy absorbing support systems in deep seismically active mining environments, value as step towards control of rockbursts, and value as a decision-making criterion for executives.

2 CHAPTER 2: LITERATURE REVIEW

At the current mining depths, seismicity and associated rockbursts are prevalent due to the high stresses to which excavations and the surrounding rock mass are subjected (Gong et al 2012; Zhang et al, 2012; Durrheim et al, 2006; Ortlepp, 1997; Johnson, 1995 & Lenhardt, 1992). This is a challenge that the Far West Rand mines are currently facing and likely to continue experiencing, and one that will affect the platinum sector as it deepens. During a seismic event, the rock mass stress equilibrium is disrupted by transient stress changes and dynamic energy is released from the rock mass as transient shock waves (Brady & Brown, 2006). These dynamic energy changes have the potential to manifest as rockbursts upon interaction with the rock mass on the periphery of excavations.

This chapter reviews what seismic events and rockburst events are, and the direct and indirect financial consequences associated with rockbursts. These financial consequences can be managed strategically with energy absorbing support systems in mining layouts optimised for dynamic loading environments.

2.1 Seismicity and Rockbursts in Mining

Deep level hard rock South African mines are prone to mining induced seismicity due to the high stresses exerted on open excavations and geological structures. Mining-induced seismicity is caused by a change in stress that results in the activation of existing geological features or the formation of new rupture planes (Heal, 2010). Excavation of rock material may cause imbalances in the stress field. This imbalance results in transient energy changes that upset the initial static state of equilibrium (Brady & Brown, 2006). This transient energy is always higher than the final static energy, consequently resulting in inelastic dynamic failure of the rock mass. This inelastic dynamic failure of the rock mass is called a rockburst and is often characterised by violent ejection of rock mass from the periphery of excavations (Stacey, 2011; Brady & Brown, 2006). Below are definitions of seismicity and rockbursts.

2.1.1 Seismic event

A seismic event is a transient stress wave caused by inelastic deformation that occurs within a given volume of rock (Owen, et al., 2002). It is characterised by a sudden radiation of energy associated with ground waves induced by slip or rock material failure (Brady & Brown, 2006). It is often accompanied by unstable energy redistribution and displacement of excavation walls (Brady & Brown, 2006).

2.1.2 Rockburst

Seismic waves may result in violent ejection of rock mass on the periphery of an excavation. The damage is due to inelastic dynamic failure of the rock mass at the periphery of the excavation and is called a rockburst (Stacey, 2011; Brady & Brown, 2006). Thus, a rockburst is the displacement of rock mass due to a seismic event. Figure 2-1 below shows rockburst damage after a seismic event. In the figure, both sidewalls and their support units experienced substantial damage.

Figure 2-1: Rock material ejected from sidewalls during a rockburst event (Mine X, 2016f)

Classifications of rockbursts

A rockburst can have of either one of the two fundamental failure mechanisms, a slip failure or a crush failure. Classifications of rockbursts are shown in Table 2-1.

Crush failure rockbursts. Crush failure is the crushing of highly stressed rock mass (Reimer & Durrheim, 2011; Board, 1994). Crush rockbursts are often associated with lower magnitude seismic events and are often characterised by coincident source and damage location (Stacey, 2011; Ortlepp & Stacey, 1994). Examples of crush rockburst events include strainburst, buckling, face crush and pillar crush. A strainburst is the superficial spalling of often sharp-edged rock fragments at high velocity. Strainbursts are common in intact brittle rock with high uniaxial compressive strengths; as such, materials have the capacity to allow stress build up (Stacey, 2016a; Ortlepp, 1994).

Slip failure rockbursts. Slip rockbursts are due to shear failure of rock material along a plane of weakness (Ortlepp, 2001; Board, 1994) or formation of a rupture through intact rock (Heal, 2010). The source and damage location of these rockbursts are usually separated by a significant distance and are often characterised by a higher local magnitude (Stacey, 2011; Ortlepp, 2001; Ortlepp & Stacey, 1994). Examples of the slip rockburst mechanism include shear rupture and fault slip as shown in Table 2-1. During a shear-rupture type rockburst, a shear fracture forms and propagates through intact rock generating seismic waves resulting in violent ejection of rock material. Fault slips are associated with redistribution of stress along existing geological features (Brady & Brown, 2006; Stacey & Rojas, 2013). During slip failure, a seismic wave is generated, which then travels out to interact with rock mass around excavations. This interaction may result in sudden ejection of rock material around the excavations.

Table 2-1: Classifications of rockbursts (Ortlepp, 2001; Ortlepp & Stacey, 1994)

Rockburst failure mechanism	Type of Rockburst	Postulated source mechanism	First motion from seismic records	Richter Magnitude M_L
Crush	Strainburst	Superficial spalling with violent ejection of fragments	Usually undetected, could be implosive	-0.2 to 0
	Buckling	Outward explosion of large slabs pre-existing parallel to surface of opening	Implosive	0 to 1.5
	Face crush / Pillar burst	Violent expulsion of rock from tunnel face or pillar sides	Mostly implosive and complex	1.0 to 2.5
Slip	Shear rupture	Violent propagation of shear fracture through intact rock mass	Double-couple shear	2.0 to 3.5
	Fault slip	Sudden renewed movement on existing fault or dyke	Double-couple shear	2.5 to 6.0

2.2 Rockburst Risks in Mining

In this section rockburst risks and their financial consequences will be reviewed. The section will first elaborate on risk in mining terms and then on risk assessment as a means of managing rockburst risk.

2.2.1 Risk in mining terms

A hazard is defined as an event that has the potential to cause harm (Oxford English Dictionary, 2016). A rockburst is a hazard. Risk is the term used to describe the relationship between probability and consequence. Rockburst risk is the probability of experiencing a rockburst with a particular extent of damage or consequence. In this research, financial consequences and losses associated with rockburst risk are of primary interest. Rockburst hazard exposes an operational mine to financial risks and possibly negative financial consequences.

Financial risks are risks that can cause a mine to not achieve its financial expectations, resulting in actual financial returns being less than the expected or planned financial returns (Rwodzi, 2011; Chakravarty, 2006). High financial risks are undesirable in a capital-intensive project such as a mine, as they represent a potential for significant financial and personal loss if the risk is not adequately managed. It is therefore in all stakeholders' interests to minimise these financial risks. In operational mines, the operational and technical risks influence the magnitude of the financial risk. Engineering design influences the technical risks.

Rockburst risks are greater in deep operational underground gold mines in South Africa compared to other commodities, due to the high seismic activity in the Witwatersrand basin. Van Aswegen & Mendecki (1999) state that the greatest threat to mine safety and infrastructure is strong ground movements resulting in rockbursts. At this stage, seismicity and rockbursts are operational risks that may result in negative financial consequences. To minimise financial risks and financial consequences of rockbursts, operational and technical risks should be managed through a suitable mine layout design and rock engineering.

2.2.2 Rockburst risk evaluation and management

Risk management is the anticipation and evaluation of a particular risk together with identifying measures to avoid or minimise its impact (Oxford English Dictionary, 2016) Figure 2-2 presents a simplified risk management model. Risk analysis, evaluation and treatment are of greater relevance in this study, as the study is about quantifying, evaluating and treating financial consequences of rockburst risks. With reference to Figure 2-2, access tunnels in deep level Far West Rand gold mining are the context; rockburst risks are the identified risks, financial consequences are what is to be analysed and then evaluated against the predetermined risk appetite; the rockburst risks are then treated with energy absorbing support systems.

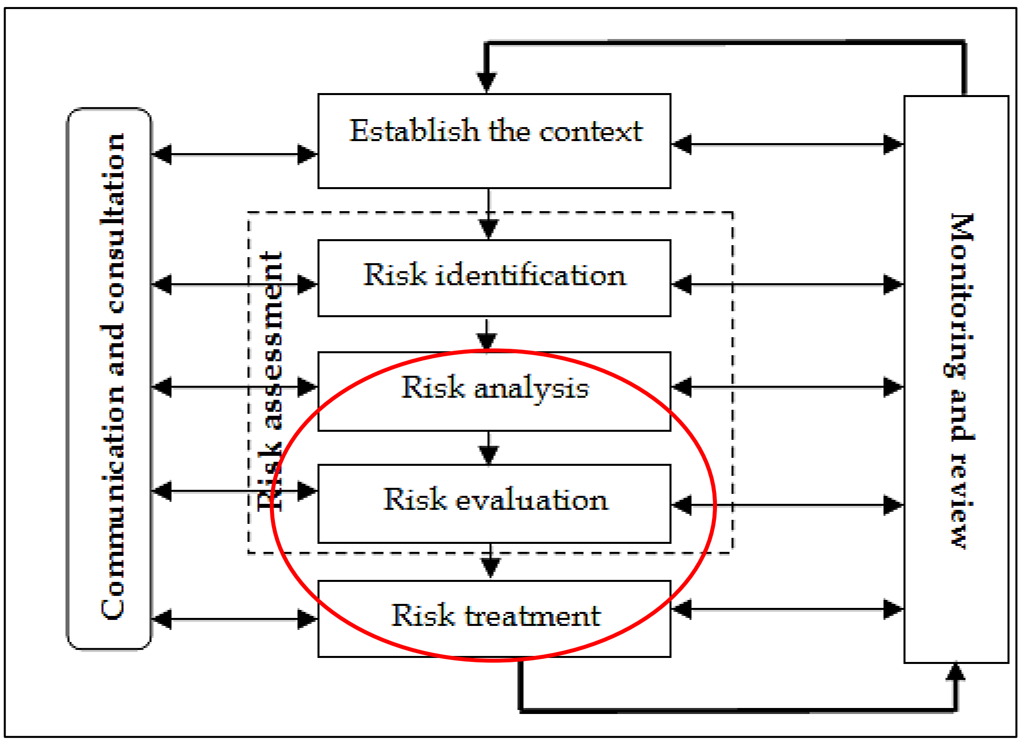


Figure 2-2: Risk management principles (De Oliveira, et al., 2017)

Rwodzi (2011) states that risk can be quantified either qualitatively, quantitatively or semi-quantitatively. Qualitative risk estimation uses observation, experience and judgement to estimate the magnitude of risk, while quantitative risk assessment applies available information and stochastic simulations to estimate risk (Rwodzi, 2011).

Principles of quantitative risk estimation are implemented in order to eliminate subjective judgement (Rwodzi, 2011). In this dissertation, quantitative methods are used to quantify consequences of rockburst risk.

Figure 2-3 represents various steps in a risk evaluation process for a risk based mine design (Joughin et al, 2011; Stacey et al, 2007; Steffen et al, 2006). The risk evaluation process is used to analyse and evaluate the risks in mine design. The quantified rockburst consequences will be evaluated against a risk tolerance matrix as used on mines.

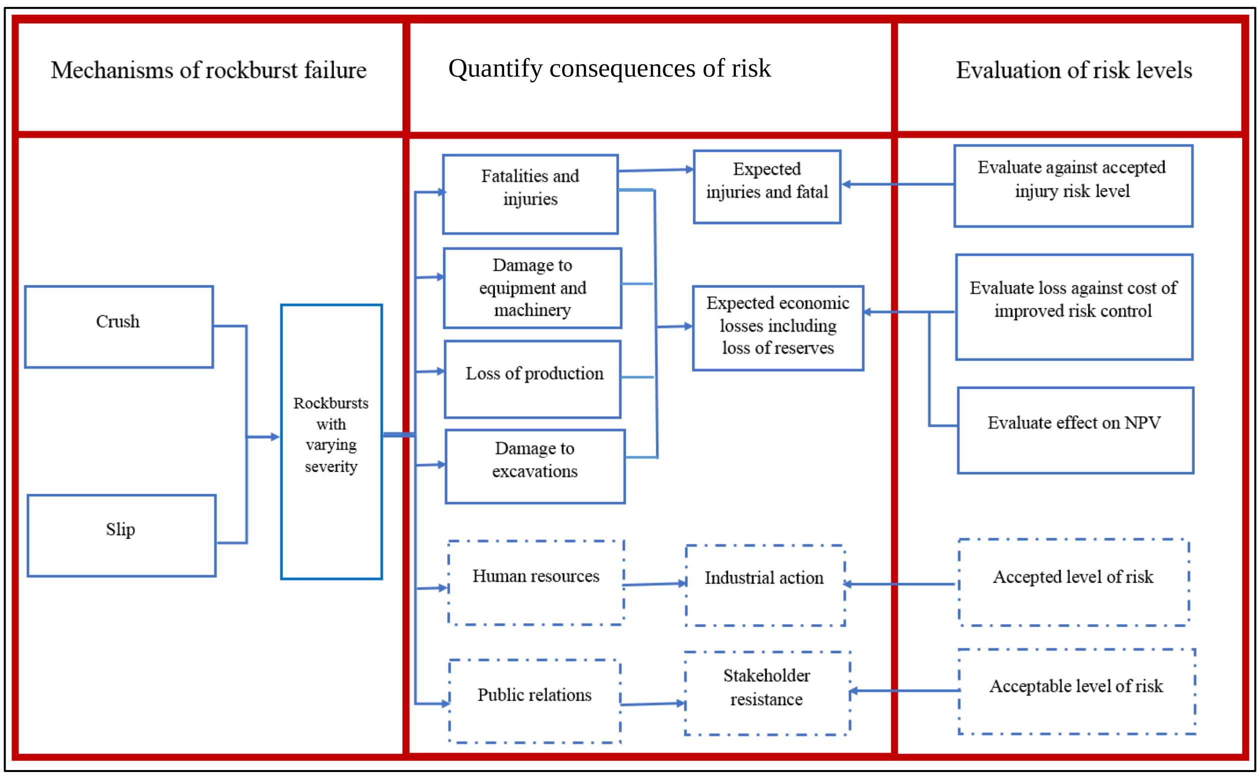


Figure 2-3: Risk evaluation process for rockburst, Adapted from Joughin et al (2011) and Stacey et al (2007).

Rockburst risk evaluation

The Safety Tripartite leadership, comprising of representatives of the state, employers and organised labour, set milestones to reach zero harm in the country's mining industry (Chamber of Mines of South Africa, 2016; Mining Qualifications Authority & Mine Health and Safety Council, 2008). However, in South African deep conventional and labour intensive mines, zero harm is an unrealistic goal. Unless the mines become fully mechanised, a realistic level of acceptable risk should be defined (Stacey, 2006).

The As Low as Reasonably Practical (ALARP) principle shown in Figure 2-4 and risk matrix as shown in Figure 2-5 are examples of risk evaluation tools used to define the level of risk that can be tolerated and help define realistic levels of acceptable risk. Once risk is analysed and its magnitude estimated, it is then evaluated against the predetermined acceptable levels of risk.

Acceptable risk is the "level of personal and/or material loss from an industrial process that is considered tolerable by society or authorities in view of the social, political and economic cost-benefit" (Business Dictionary, 2017). Presented in Figure 2-4 is an ALARP model used to evaluate acceptability of risk. "Reasonably practical" is influenced by the economic cost benefit as determined by stakeholder tolerance (Rwodzi, 2011). It is generally accepted that an operation should keep its risk at tolerable risk and below (Rwodzi, 2011).

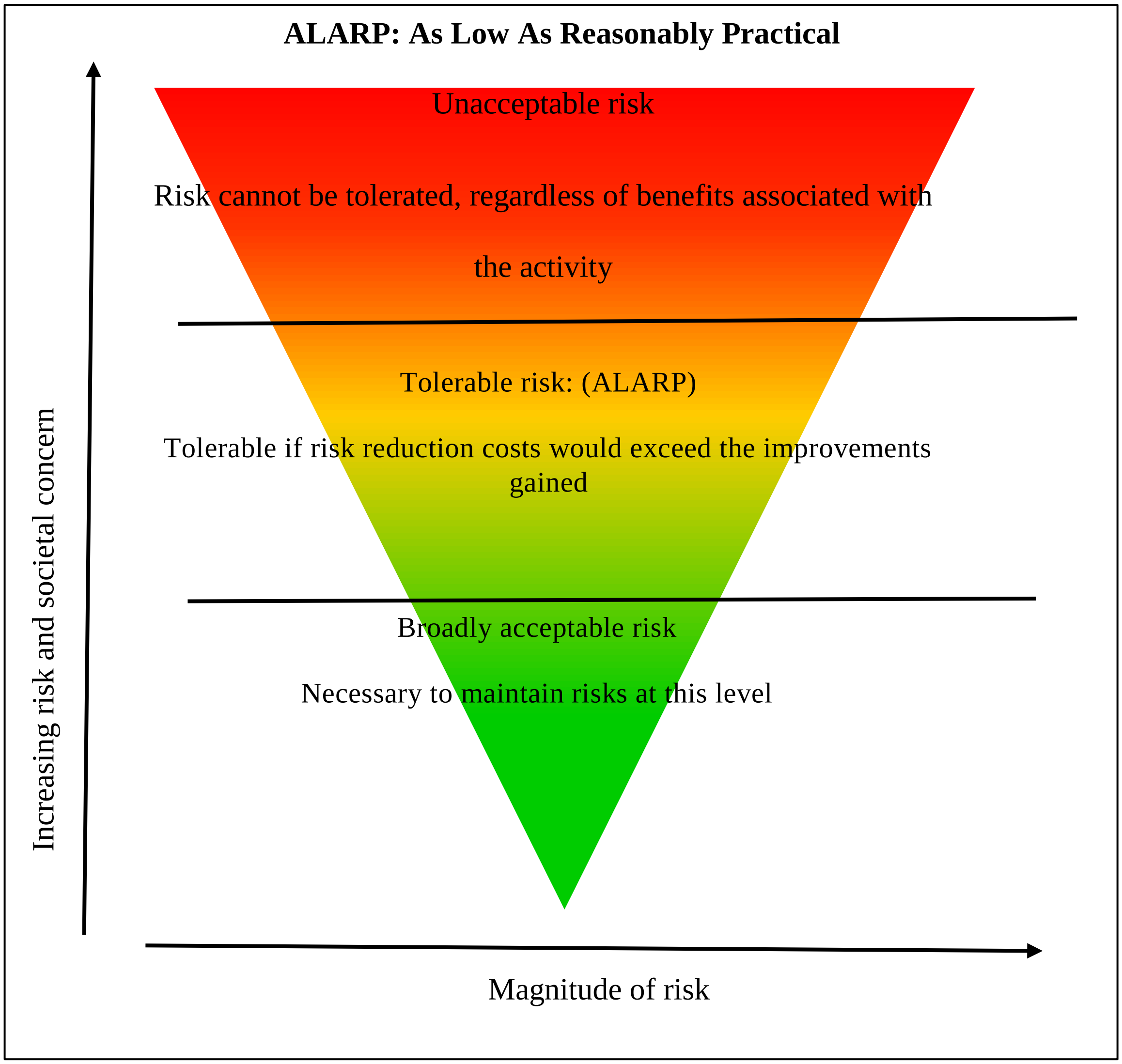


Figure 2-4: As low as reasonably practical principle (Rwodzi, 2011).

Risk is often classified as high, medium or low, depending on its probability of occurrence and the magnitude of consequences. Once a risk is estimated, evaluated and classified, risk treatment is implemented. Management can decide to accept, reduce, transfer or avoid the risk, depending on the magnitude of the risk and stakeholder risk appetite. Figure 2-5 is an adaptation of the risk evaluation matrix used at one of the mines (Mine X, 2016g). This matrix is adapted for smaller scale analysis, i.e. for a mine section instead of an entire shaft. This makes evaluation of the case studies collected easier and within similar scale.

Consequences (impact) are classed as extreme, major, high, moderate, minor or insignificant. Each of these consequence classes correspond to an estimated range of financial loss. The limits or bounds of each financial loss class are influenced by stakeholder risk appetite. The frequency of a risk is classified as either almost certain, very likely, likely, unlikely but possible, very unlikely or almost impossible. The frequencies corresponding to each frequency class can be estimated from historic data. For instance, less than 4% of seismic events resulted in rockbursts in access tunnels at Mine Y. Rockburst risks with risk classification ranging between 16 and 36 are to be managed with energy-absorbing (dynamic) support systems while risk with classification below 16 can be managed with rigid support systems.

Negative impacts		***Risk Classification*** *(Risk Index):*					
Impact Class	Financial loss						
Extreme	> R 50 million and/or multiple fatalities	21	30	32	34	35	36
Major	R 10 million - 50 million and/or Fatal, multiple disablement	17	27	28	29	31	33
High	R 1 million - 10 million and/or Permanent disability	14	22	23	24	25	26
Moderate	R 100000 - 1 million and/or Temporary disability	8	15	16	18	19	20
Minor	R 10000 - 100.000 and/or Medical treatment case	2	9	10	11	12	13
Insignificant	<R 10 000 and/or No injury	1	3	4	5	6	7
Frequency (probability):		<1%	1-33%	33-50%	50-66%	66-96%	96-100%
Frequency (class):		***Almost impossible***	***Very unlikely***	***Unlikely but possible***	***Likely***	***Very likely***	***Almost certain***
		Likelihood (of rockburst event in a section)					

Risk Classification:	**Support System**
(31-36)	Steel sets
(25-30)	Dynamic support
(16-24)	Dynamic support
(9-15)	Static support
(1-8)	Static support

Figure 2-5: Risk evaluation matrix adapted from (Mine X, 2016a)

In conclusion, risk assessment and treatment include quantifying the probability of a rockburst occurrence, the magnitude of rockbursts consequences and method used to manage/treat the rockburst risk. The risk appetite of stakeholders influences the significance of the risk. Once the significance of the risk is determined, a suitable support system is chosen to treat the rockburst risk. However, determining the probability of experiencing a rockburst event is beyond the scope of this research. The focus will be on quantifying consequences of rockbursts, using energy absorbing support systems to treat rockburst risk, and developing a model to evaluate the magnitude of the consequences.

Rockburst risk identification and analysis

Quantitative risk analysis is characterised by two key parameters, namely quantifying probability of occurrence and quantifying magnitude of consequence. This section will focus on quantifying consequences of rockbursts, as quantifying probability of rockbursts is beyond the scope of this dissertation.

Magnitude of consequence

The second step in the risk evaluation process in Figure 2-3 is to quantify identified consequences of rockbursts. Stacey & Rojas (2013), Rwodzi (2011) and Joughin et al (2011) have identified and grouped rockfall consequences as direct and indirect. Table 2- 2 shows consequences of rockfalls. Rockburst consequences are similar to consequences experienced during a rockfall. Direct consequences are physical consequences that occur during the event, while indirect consequences arise because direct consequences occurred. Indirect consequences are negative financial implications of rockbursts. For the purpose of this study, indirect consequences are grouped into quantifiable and unquantifiable indirect consequences.

Table 2-2: Direct and indirect consequences of rockfalls (Joughin, et al., 2011)

Direct Consequences	**Indirect consequences**
Damage to excavations (access excavations and stopes)	Loss of reserves (Net present value of lost reserves less insurance claim) - major damage or loss of access to stopes.
	Loss of production (revenue from lost production less variable costs) if there is no alternate source of production.
	Replacement of access excavations (cost divided by life in years) –large rockfalls
	Rehabilitation - proportional to size of rockfall and importance of excavation
	Dilution (in stopes)
	Re-deployment of machinery and personnel to maintain production.
	Clean up operations. – (depends on size of rockfall)
	Insurance premiums – (Increase due to claims)
	Stakeholder resistance (reputation, share price and cost of capital)-difficult to quantify
Injuries and fatalities	Moral and societal risk
	Temporary mine closure (Mine Health and Safety Act, Section 54) –(revenue from lost production less variable costs) up to 5 days of partial or full mine closure. Re-training of existing personnel, audits and loss of reserves
	Medical and rescue operation costs
	Wages and compensation
	Investigation and inquiries – cost of professional time
	Re-training – cost of re-training new employees
	SIMRAC levies – (depends on severity of injury)
	Legal costs – (determined from precedent practice)
	Insurance premiums – (Increase due to accident record)
	Industrial action – difficult to quantify
	Stakeholder resistance (reputation, share price and cost of capital)-difficult to quantify
Damage to equipment and machinery (mobile and fixed)	Loss of production (revenue from lost production less variable costs) if there is no alternate source of production. - only production affected by equipment loss
	Cost of re-deployment of machinery and personnel to maintain production
	Replacement costs (based on depreciated value of damaged machinery) - large rockfalls
	Cost of repairs – depends on extent of damage (size of rockfall)

Quantifiable indirect consequences

Indirect quantifiable consequences relating to damage to access excavations, injuries and fatalities, and damage of equipment will be used to evaluate the magnitude of rockburst risk consequences.

Damage to access excavations. Access haulages are used as transportation routes for personnel, material, waste and ore. They are the link between stopes and shaft to surface, thus they need to be some of the safest excavations in a mine. However, rockbursts threaten the integrity of these haulages. This may lead to costs incurred due to rehabilitation or establishment of new accesses after rockburst damage. While the access is being rehabilitated, ore flow, material movement and/or personnel may be interrupted leading to loss of revenue. Should the rockburst be extensive, a temporary stoppage is imposed by the Department of Mineral Resources (the DMR), and the financial loss and impact on project schedule can be substantial.

Personnel injuries and fatalities. Rockbursts become a safety hazard when they occur in tunnels in which personnel are working or travelling. In severe cases, the mine will incur costs relating to investigation and rescue of personnel, legal costs relating to accidents, levies and fines. The mine may be issued with a temporary mine closure, according to Section 54 of the Mine Health and Safety Act (MHSA) of 1996, known as Section 54. It was reported that Section 54 closures cost the South African mining industry an estimated R 4.8 billion in revenue, with each stoppage costing an estimated R 13 million and lasting an average of five days (McKay, 2016; Rwodzi, 2011)

Most mining companies have safety as a first value (Harmony Gold, 2016; AngloAmerican, n.d.). Rockbursts threaten this value and have the potential to directly affect the personnel, their dependents, the operation and the industry as a whole. To uphold this value, the effects of rockbursts are to be managed effectively. There are medical costs and compensation costs incurred in the event of personnel casualties and in most cases loss of the breadwinner in the family. Chapter 4 of the Compensation for Occupational Injuries and Diseases Act (COIDA) 130 of 1993 amended 91 of 1997 states that if an employee is disabled or deceased during a workplace injury, the employee or his dependents are entitled to financial compensation. Rwodzi (2011) and Udd (2008) state that the amount paid in compensations is proportional to the personnel's wages and varies with the severity of the injury.

Damage of equipment and machinery. Damaged equipment may require repair or replacing with new equipment. All these expenses influence the cash flow of the operation.

Unquantifiable indirect costs

Rockbursts can trigger far-reaching consequences such as industrial action, reduced investor confidence, stringent law making, legal and levy costs. These costs are difficult to quantify, thus they will be excluded in this research.

Probability of occurrence

Probability is another important factor when quantifying risk. Rockbursts of different severities have different probabilities of occurrence. Each severity has different implications on the magnitude of the risk (Rwodzi, 2011). However, predicting the probability of occurrence of a rockburst event is still a challenge, as the mechanisms of mining-induced seismic events are not yet fully understood. Since rockbursts and seismic events cannot be predicted with certainty, the concept of probability of rockburst occurrence is beyond the scope of this study.

2.3 Strategies for Mitigating Rockburst Hazards

Treating a rockburst risk is a process that starts with planning, anticipating a seismic event, where possible and implementing measures to manage the risk. The following principles can be applied to rockburst risk management.

2.3.1 Rock engineering design

Rock engineering is the branch of engineering that focuses on the design and support of excavations in rocks (SAIMM, 2016). It entails the understanding of support types and their performance in various rock stress environments (SAIMM, 2016). Rock engineering implements both strategic and tactical planning strategies. A mine is a long-term project with a long-term goal of achieving financial success. A strategic plan is a broad framework of intended long-term objectives of a mine (Kear, 2006). A strategic plan identifies all possible scenarios that lead to achieving the objective (Kear, 2006). Rock engineering design is a strategic plan that can be used to effectively manage rockburst risk.

A strategic rock engineering design is carried out in three steps; first, the historic study of the area of interest, then the excavation design layout and finally, support systems as the last line of defence. These steps are discussed in this section. Seismic and history review and layout design are long-term strategic tools to manage rockbursts, whilst a support system can be both a strategic and a tactical measure depending on the expected longevity of the excavation.

Seismic review and history of mine area

During strategic rockburst risk management, a rockburst profile of the area of interest is carried out, looking at the history of the mining area, the history of the mine and of neighbouring mines. The information gained may improve the understanding of rockburst and seismic mechanisms which have the following benefits:

- can improve the approach to rockburst risk management and rock engineering design (Ortlepp, 1994)
- may lead to comprehensive mine designs and better planning (Diering, 1997)
- can improve the approach to seismic risk management (Potvin & Wesseloo, 2013)
- can help to determine which mitigation measures yield better results.

Seismic information can be obtained through three dimensional seismic surveys and review of seismic information collected through seismic monitoring of surrounding operations. For example, Manzi et al (2015) describe a seismic survey carried out at Mine X, and Mikula (2005) and Van Aswegen & Laas (2003) describe various techniques of seismic monitoring.

Geological structures

Geological structures have a major influence on mine layouts. Common geological structures associated with seismicity are dykes and faults. A large proportion of instability and seismicity is associated with geological structures as shown in Figure 2-6 (Lenhardt, 1992). Figure 2-6 shows 65% of seismic events with M_L greater than 3 occur in the vicinity of geological structures.

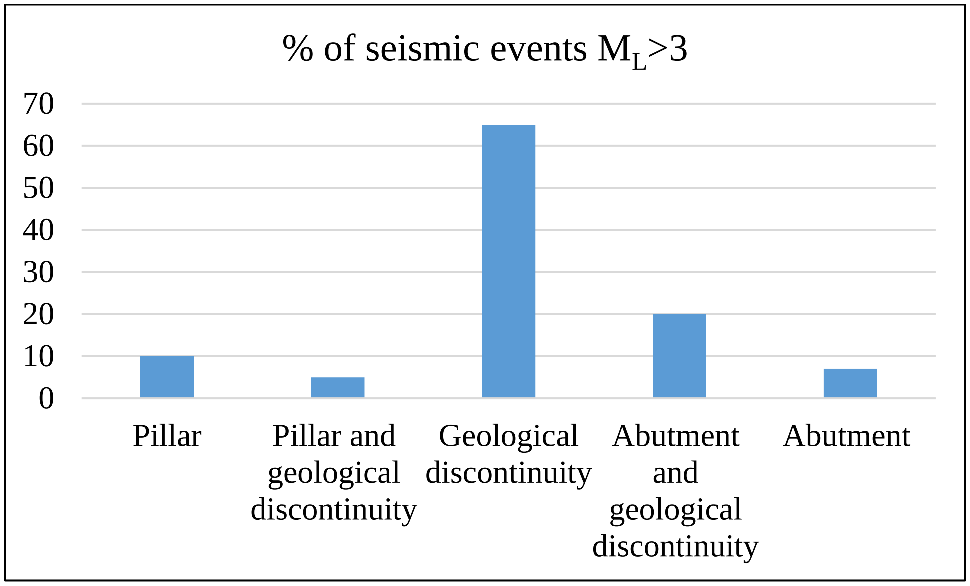


Figure 2-6: Seismicity along geological structures (Lenhardt, 1992)

Geological structures influence the location and manner in which access tunnels are developed. The positions of tunnels relative to other design factors (geological features, other tunnels, field stresses, etc.) play a role in the overall stability and stress distribution around the tunnels. It is a general rule that geological features are to be avoided where possible. In cases where it is not possible, in stoping layouts, a minimum 20 m solid bracket pillar is left on either side of the geological feature in order to maintain the stress equilibrium in the geological feature (Mine X, 2016e; Brady & Brown, 2006; Jager & Ryder, 1999). To prevent stress build-up, it is advised that mining should progress from high stress areas to low stress areas; in this case, geological features are regarded as high stress areas as they have the potential to unravel and mining should be away from the feature. Jager and Ryder (1999) recommends that tunnels be excavated parallel to and at least 50 m from geological features. In cases where they are to be intersected, they are approached at an angle as close to 90 degrees as possible in order to minimise contact with the unstable zones (Brady & Brown, 2006; Jager & Ryder 1999).

Excavation layout design

The main objective of rock engineering in tunnel layout design is to minimise deformations due to stress and to maximise stability of the excavation (Jager & Ryder, 1999). A well-designed mine layout offers strategic and tactical advantages against rockbursts (Jager & Ryder, 1999). To maximise intrinsic stability, tunnels should be excavated in the most favourable position in order to minimise rock mass deterioration. Jager and Ryder (1999) state that ideally, tunnels should be excavated in strata with high rock mass strength to maximise intrinsic stability. However, this is not always practical as it may be necessary for tunnels to traverse poor rock mass and geological structures.

<u>Excavation parameters</u>

In a mine environment, multiple mine excavations will interact with each other and where possible, this interaction should be minimised. In deep level operations where high stresses are anticipated, planning should aim to maximise the separation between tunnels and/or geological structures. Jager and Ryder (1999) state that, where seismicity is anticipated, the centre to centre separation of adjacent excavations should be greater than three times the sum of the widths of the two tunnels. Figure 2-7 below summarises parameters to consider when designing tunnels. A breakaway (for example, a bullnose of a crosscut and main haulage) should not be less than 45°. Two successive breakaways should have a separation equivalent to at least six times the tunnel widths.

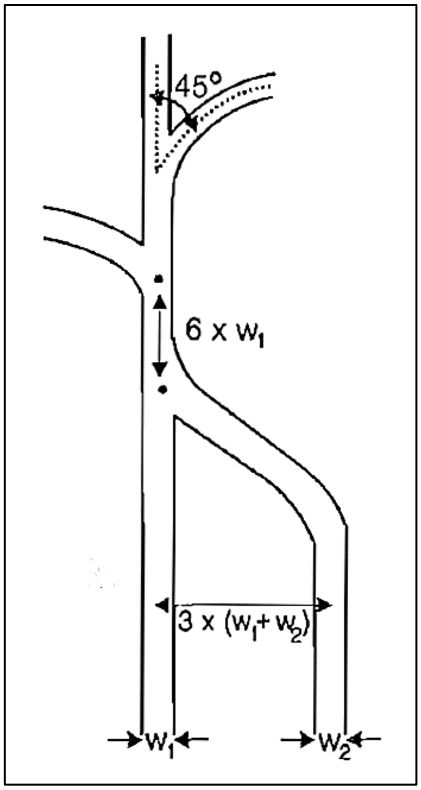


Figure 2-7: Layout of tunnels to avoid stress interactions between access excavations (Jager & Ryder, 1999).

Excavation size and shape

Jager and Ryder (1999) state that the geometry of an excavation is proportional to the degree of stress concentration on the tunnel. In arched tunnels, the excavation is stabilised by compression due to high tangential stresses (Yilmaz, 2015). Horizontal stresses induce compressive stresses in the tunnel roof thus improving the stability and integrity of the tunnel roof significantly (Daehnke, et al., 2000). Arched tunnels reduce the area exposed to high vertical stresses

Support systems

A rock support system is a rock engineering strategy used as a last line of defence against excavation instabilities. This research focuses on underground support systems for access tunnels subjected to dynamic loading. Underground support systems are discussed comprehensively in section 2.4.

2.4 Underground Support Systems

In a mining environment, rock engineering deals with preserving the integrity and stability of the rock mass around open excavations. As discussed earlier, seismic review, mine design layout, and support design are integral to excavation stability in a seismically active environment. In this section, underground support systems are discussed. Support systems are likely to be effective in a well designed mine layout. In underground mining, support is used to improve stability and the load carrying capacity of the rock mass around excavations (Brady & Brown, 2006). The primary function of support is to conserve or enhance the inherent strength of the rock mass so that the rock mass around an excavation can continue to be self-supporting (Hoek & Wood, 1987). The objective of conserving the self-supporting properties of a rock mass is to:

- Ensure the safety of personnel
- Protect machinery and equipment
- Keep access open to allow movement of tonnages, equipment and personnel

By ensuring the above objectives, the operation remains productive at optimum costs (Erasmus, et al., 2009).

Support can be categorised as either primary or secondary support. Primary support is installed during or immediately after excavation, to ensure safe working conditions and to preserve the integrity of exposed rock mass (Yilmaz, 2015). Primary support is commonly reinforcement support used to improve or preserve properties of the rock mass. Secondary support is installed at a later stage to complement the primary support. Support can be further classified into active and passive support. Active support exerts a predetermined magnitude of force to the rock mass (Yilmaz, 2015). Passive support is reactive; it starts to exert force once the rock mass starts to deform (Yilmaz, 2015).

During a rockburst, the rock mass fails under dynamic loading due to the transient energy changes radiated from the seismic event. Support with energy absorbing capabilities is necessary to absorb the transient energy changes and prevent or minimise violent failure of the rock mass around excavations. An energy absorbing support system will yield and absorb the energy when subjected to dynamic stress changes, thus increasing the stress carrying capabilities of the surrounding rock mass. The purpose of energy absorbing support system is to increase the rock mass' capacity to withstand transient stress changes during a seismic event.

2.4.1 Types of support units

Different types of support are suitable for different mining conditions. In deep level gold mines with prevalent seismicity and consequently rockbursts, it has been determined that energy absorbing support is the most suitable as it yields under dynamic stress (Stacey, 2013; Brady & Brown, 2006). This section will look at different types of support elements with energy absorbing capabilities. Figure 2-8 shows energy absorbing properties of support components and maximum associated deformation. Chain-link mesh, and straps or rope lacing have the highest deformation limit and high energy absorbing capabilities (Stacey, 2016a; Stacey & Ortlepp, 2001).

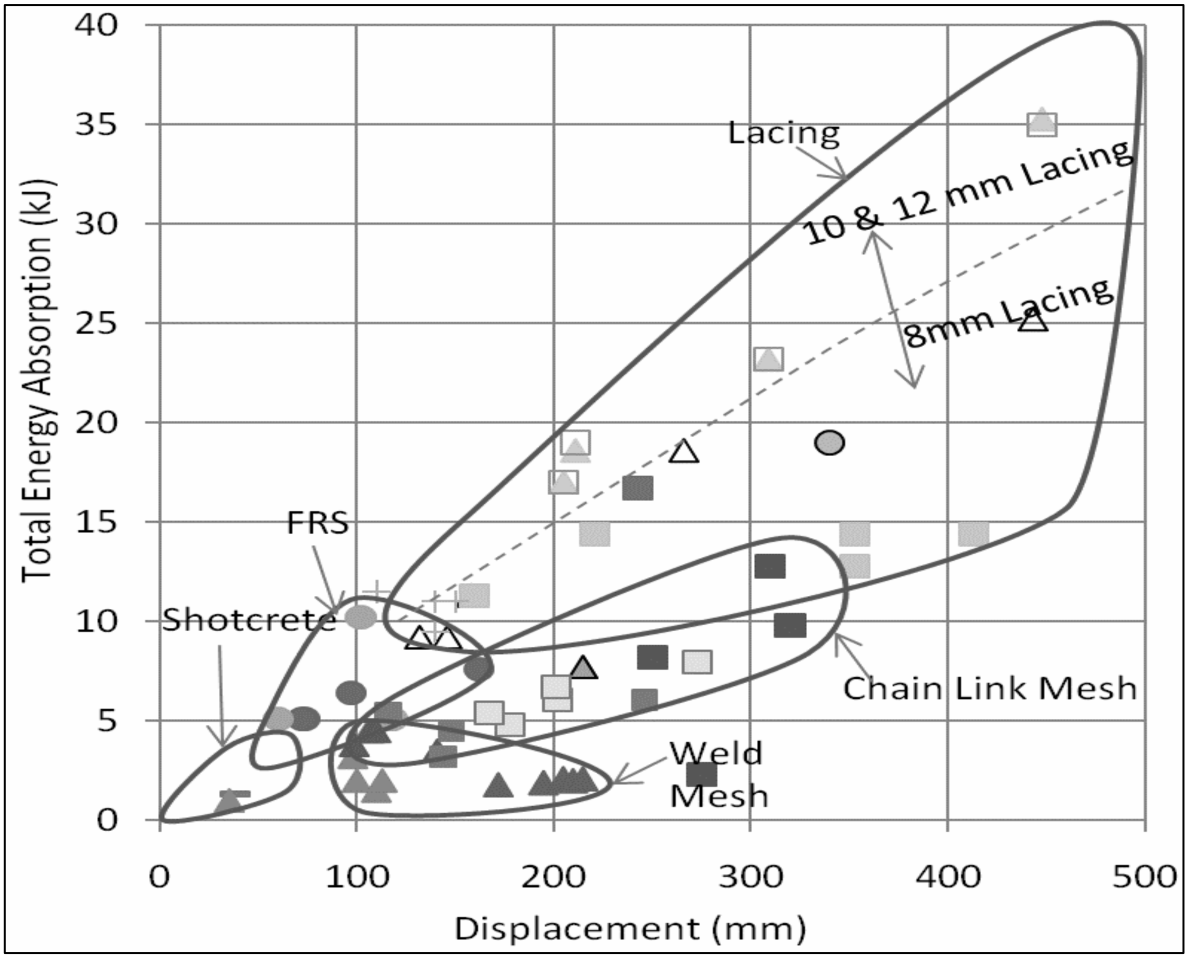


Figure 2-8: Results of simulated dynamic testing of support units (Stacey, 2016b)

Tendons

Tendons are active support elements installed either as temporary or permanent support. When used as permanent support, they can be cement or resin grouted in order to improve the pull out strength and reduce susceptibility to corrosion (Brady & Brown, 2006). Tendons provide constraints to rock mass failure and thus help in maintaining the integrity of the rock mass. Li, Stjern and Myrvang (2014) define two classifications of tendons, namely conventional/rigid and energy absorbing/yielding. Rigid tendons include mechanical rock studs, full column grouted reinforcement bars and friction bolts (Li, et al., 2014). Energy absorbing tendons are intended for managing dynamic energy changes associated with rockbursts. They have the capacity to yield up to predefined peak loads. The tendons yield by slippage or stretching mechanisms (Li et al, 2014; Ansell, 2005).

Figure 2-9 presents performance of different tendons when subjected to a pull load. Rebars, expansion shell bolts, inflatable bolts and splitsets are categorised as conventional or rigid tendons. Examples of energy absorbing yielding tendons include conebolts, Garford solid bolts, Roofex, D-Bolts, Yield-lok bolts and Durabar yieldable tendons. Durabars are commonly used in the South African mining industry. Yielding tendons have a high load carrying capacity and can deform to accommodate significant rock mass movement before they fail. They have the capacity to carry a load close to or equal to the strength of the bolt material (Li, et al., 2014). Effectively, a yielding tendon can carry a load for a large displacement at its peak pull-load capacity. The tendon will yield within its load carrying capacity and its yielding resistance will arrest the failing rock mass into a new stress equilibrium; or the tendon will exceed its maximum load carrying capacity before absorbing all the dynamic energy and will fail violently (Ortlepp & Swart, 2002).

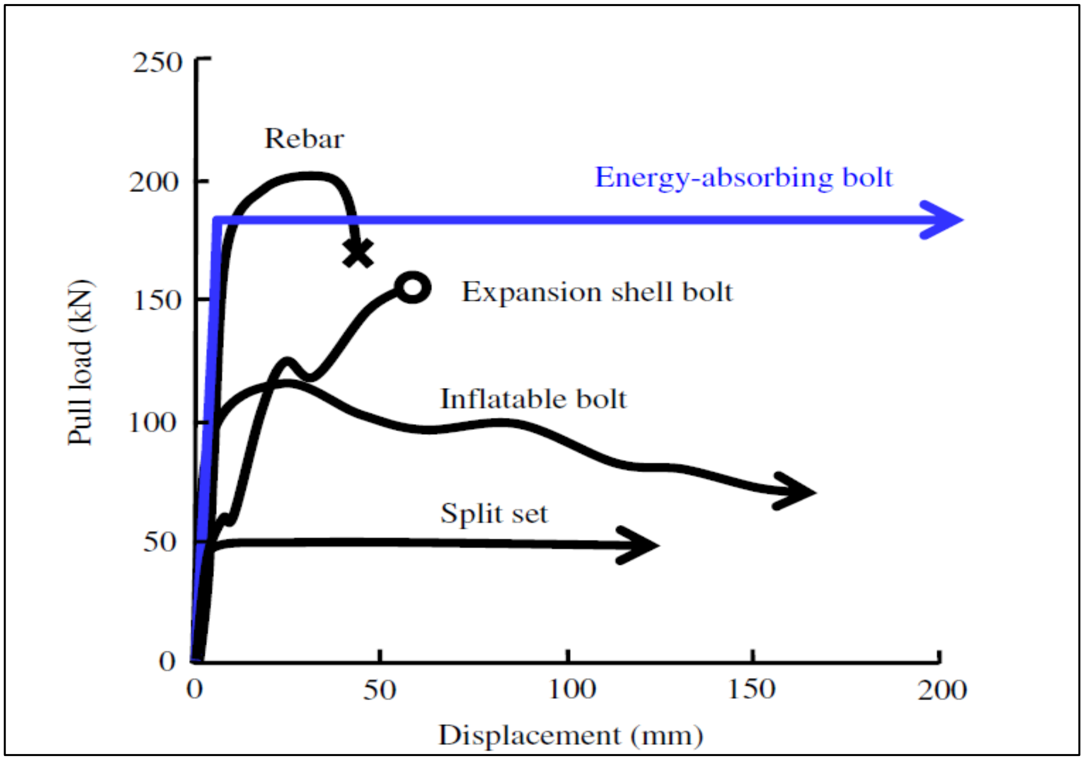


Figure 2-9: Performance of different rock bolts when subjected to pull loading (Li, et al., 2014)

The performance of tendons is influenced by the type of nuts and faceplates used in conjunction with the tendons. Faceplates help with the transfer of load from the tendon to the rock face. If the faceplate fails, the tendon loses the capability of retaining the rock material, which leads to the tendon being unable to provide reinforcement (Stacey, 2016b). Faceplates can also be used to clamp containment support (mesh) in place. Deb (2012) shows that tendons with faceplates experience reduced radial displacements of rock mass by 25% while tendons without faceplates experience displacement reduced by only 15%.

Skin support

In tunnel excavations, shotcrete is used to prevent unravelling and deterioration of the rock mass on the surface of the excavation (Potvin & Hadjigeorgiou, 2008; Brady & Brown, 2006; Hoek & Wood, 1987). It is used to fill the cracks formed in the rock mass on the periphery of excavation; this improves the inter-locking and self-supporting properties of the rock mass (Hoek & Wood, 1987). Shotcrete is a mixture of cement, water and/or reinforcement (Brady & Brown, 2006). Shotcrete is applied pneumatically in a continuous stream to maximise compaction while minimising overspray and rebound of the mixture (Hoek & Wood, 1987). The quality and durability of the shotcrete depends on the skill of the operator as well as the material used (Brady & Brown, 2006).

To improve strength and resistance to shock, shotcrete can be reinforced with steel fibre, polypropylene fibre or micro-silica (Brady & Brown, 2006). Micro-silica improves resistance to corrosion and reduces rebound of the shotcrete during application (Sharma, 2015). Steel and polypropylene fibre reinforcements improve the load carrying capacity of the shotcrete after cracking (failure) (Hoek & Wood, 1987). Correctly applied reinforced shotcrete can withstand large deformations before it fails (Stacey, 2016b; Brady & Brown, 2006; Stacey & Ortlepp, 2001). In deep level mines, it is commonly applied at a minimum thickness of 50 mm (Mine X, 2016b; Mine Y, 2016a; Murphy, 2002). In some cases, thin spray-on liners can be used instead of shotcrete. Thin spray- on liners showed better response to tensile and shear bond stress when compared to shotcrete (Yilmaz, 2009; Yilmaz, 2007) and are able to withstand larger deformations when compared to shotcrete.

Mesh and lacing

Wire mesh is a passive support as it provides resistance only when deformation starts to occur. It is an areal support that provides coverage of the rock mass between tendons, it can retain loose rock on the periphery of the excavation after a rockburst (Brady & Brown, 2006). The wire mesh is expected to absorb energy released during the seismic event and to contain failed rock material without failing. Rope lacing is used to tighten the mesh, to improve the energy absorbing capacity of the mesh and to restrain movement of loosened rock mass (Brady & Brown, 2006; Ortlepp, 2001; Stacey & Ortlepp, 2001). The benefits of lacing as a component of dynamic support are illustrated in Figure 2-8, which shows that lacing has the capacity to absorbing high energies and high material displacement. The figure also shows that chain-link mesh has the second highest capability of absorbing energy and displacement. Chain-link mesh has flexibility and has potential to absorb dynamic energy released during a seismic event (Stacey & Ortlepp, 2001). Current design requirements for energy absorbing capabilities in wire mesh include high tensile strength and wire that exhibits elastic deformation during loading (Geobrugg, 2016).

Steel sets

Steel sets are passive support mechanisms used where high load carrying capacity is required. They are suitable for tunnels, especially in poor rock masses developed within faults, dykes and shear zones (Hoek & Wood, 1987). Steel sets are permanent support for long-term tunnels subjected to high stress and where movement of the rock mass is continuous (Hoek & Wood, 1987). In areas where rockbursts are prevalent, yielding steel arches can be used to accommodate deformations (Brady & Brown, 2006). Coupled with other support components, yielding steel arches can be suitable for high rockburst risk environments, as they have the ability to yield to dynamic stress changes associated with the rockbursts. Brady & Brown (2006) state that the effectiveness of steel sets is proportional to the quality of the voidfill material. Voidfill material facilitates uniform transfer of load from the rock mass to the steel sets and it absorbs the shock energy released during a rockburst (Ras, et al., 2007). In rockbursting environments, foamcrete is the preferred voidfill. Foamcrete is a porous concrete mixture of cement and a significant volume of air (Ras, et al., 2007). Due to its porosity, foamcrete has a low density, thus exerting little stress on the steel sets, and is able to absorb dynamic energy.

2.4.2 Support Systems

A support system is a combination of different support components that complement each other. A combination of the above support units will likely provide an effective support system during a rockburst. An energy absorbing system should have both reinforcing and retaining properties. For a tunnel, the support systems described below are proposed:

Yielding support system

Ortlepp & Swart (2002) state that a dynamic support system should have the following four essential elements:

- Tendons of sufficient length and yieldability,

- Areal confinement,
- Strong linear element to back up the mesh,
- Linear elements to couple the tendons.

The yielding system takes advantage of the tendons and chain-link mesh's ability to yield under stress. The system comprises of yielding tendons, tendon straps, long anchors, chain-link mesh with lacing and a layer of skin support (Stacey & Ortlepp, 2001). Figure 2-10 shows a yielding support system installed in an access tunnel.

Figure 2-10: An example of dynamic support system (Mine Y, 2015)

Yielding set support system

A steel set support system is suitable for weak and jointed rock conditions associated with geological features such as faults and dykes. It is often installed where the access tunnel has a known history of seismicity, is a main haulage or is the only access to a profitable raise line. This system will include yielding tendons and long anchors to provide reinforcement; chain-link mesh with lacing and yielding sets with foamcrete for voidfill to provide passive and retaining properties of the system. Figure 2-11 and Figure 2-12 show a yielding set support system.

Figure 2-11: Ring steel set support system (Mine Y, 2015)

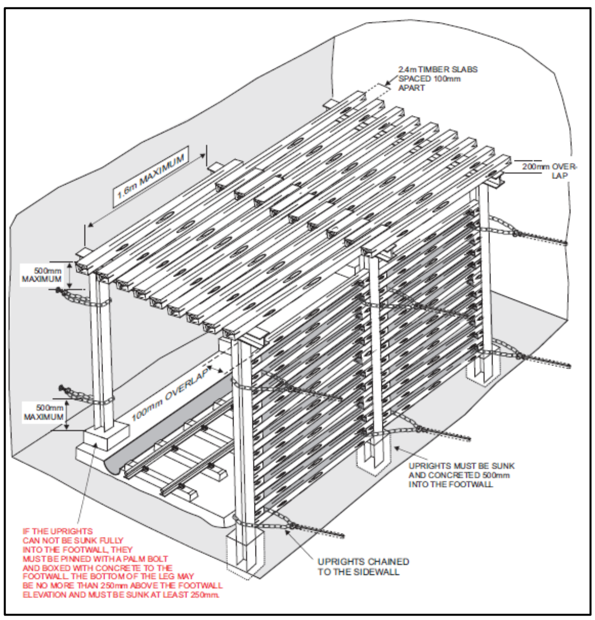


Figure 2-12: Schematic presentation of set installation (Mine Y, 2016b)

Figure 2-13 shows a representation of an I-beam set support system that is considered a less costly version of the yielding set support system. This system consists of rigid tendons, long anchors, I-beams and wooden laggings and sometimes voidfill. This system is a rigid variation of the set support system.

Figure 2-13: I-Beam set support system (Mine X, 2009)

Rigid support system

For the purpose of this study, this system will include rigid tendons and long anchors to provide reinforcement; spiral bound welded mesh and a layer of shotcrete. This system is suitable for environments under static loading conditions. Figure 2-14 shows an example of an installed rigid support system.

Figure 2-14: Installed rigid support system (Mine Y, 2015)

The stress environment informs the choice of support system. Support systems with yielding properties are suitably for yielding environments while rigid support systems are suitable for shallow mining environments under static stress.

2.5 Summary

In this chapter, the following issues are outlined:

- the difference between seismic event and rockbursts ,
- rockburst as a risk and (financial) consequences associated with the rockburst risk.

Rock engineering design was identified as a strategy for mitigating these risks. Rock engineering design strategy comprises of analysing the following: seismic review, influence of geological structures, excavation design and layout, and implementation of appropriate support systems. Energy absorbing support systems are of greater relevance given that the research is based on the seismically active Far West Rand operations.

3 CHAPTER 3: FORMULATION OF EXCEL MODEL

This chapter will focus on developing an Excel model to evaluate financial impacts of the indirect consequences of rockbursts and the financial value added by different support systems. The primary inputs into the Excel model are financial losses associated with rockbursts in access tunnels, lost revenue due to interrupted ore flow, and costs associated with personnel casualties. As a strategy for rockburst risk treatment, support systems were theoretically implemented in case studies and their costs estimated to determine their financial impacts.

An Excel model named the Consequence-Quantifying model was developed to help quantify financial consequences in the case studies. The model uses information from rock engineering reports, health and safety reports, recommendations and material catalogues to estimate the financial consequences of rockbursts. The consequence-quantifying model has three versions, namely the executive spreadsheet, the engineer spreadsheet and the primary spreadsheet. The executive spreadsheet is intended for executives and can be used to give an overview of the financial impact of the rockburst. The engineer spreadsheet is intended for the technical person and can be used for support design and optimisation. The primary spreadsheet can be customised to suit different support installation practices and can be used to facilitate back analysis after a rockburst event.

3.1 Data Collection

Seven weeks were spent collecting data at two Far West Rand deep level gold mines, which will be referred to as Mine X and Mine Y, due to confidentiality reasons. Rock engineering reports pertaining to rockburst incident investigations were collected and catalogued. These reports formed a basis for a rockburst database for this research. From this database, case studies of interest were chosen based on comprehensiveness of the information within the report and the year of the incident. Reports that had complete information and rockbursts that occurred within the last ten years were preferred as they are likely to show recent support installation practices. The cost of the rockburst and material used in the operation were collected from the Finance Department at the mines.

Statistics relating to Section 54 mine closures and personnel casualties were collected from the Health and Safety Department. Statistics relating to ore movement and off reef developments were collected from the Survey and Production Departments.

3.1.1 Site background

The mines are both deep level gold mines in the Far West Witwatersrand basin. The Witwatersrand basin is experiencing high seismic events and has the highest seismic activity of all the different mineral fields in the country, accounting for 73% of 2016 seismic events (Council for Geoscience, 2016).

Ore production at Mine X takes place between 2.4 km and 3.4 km below surface and the mine is currently being deepened to 4 km below surface (Mine X, 2016g). The mine currently exploits the Vendersdorp Contact Reef (VCR), with the mine-deepening project underway targeting the Carbon Leader Reef (CLR) 500 m below the VCR. The VCR operations are accessed via a surface shaft and a subterranean shaft system (sub-shaft), while the CLR is accessed via a ramp from the bottom level of the sub-shaft. The sequential grid mining method is used to mine the VCR reef (Mine X, 2016e; Murphy, 2012). Remnant pillars are left behind and backfill is used as regional support to control stope closure (Jager & Ryder, 1999). This is a better mining layout as it provides greater flexibility and improved stability of mined-out areas.

Figure 3-1 shows a plan view of a sequential grid mine layout implemented at Mine X. The structures indicated in green are dykes, faults are indicated in magenta and unmined areas are indicated in grey. The grey unmined ground is concentrated around geological structures and it indicates bracket pillars around the geological structures.

Figure 3-1: Plan view of a sequential grid mining layout (Mine X, 2016f)

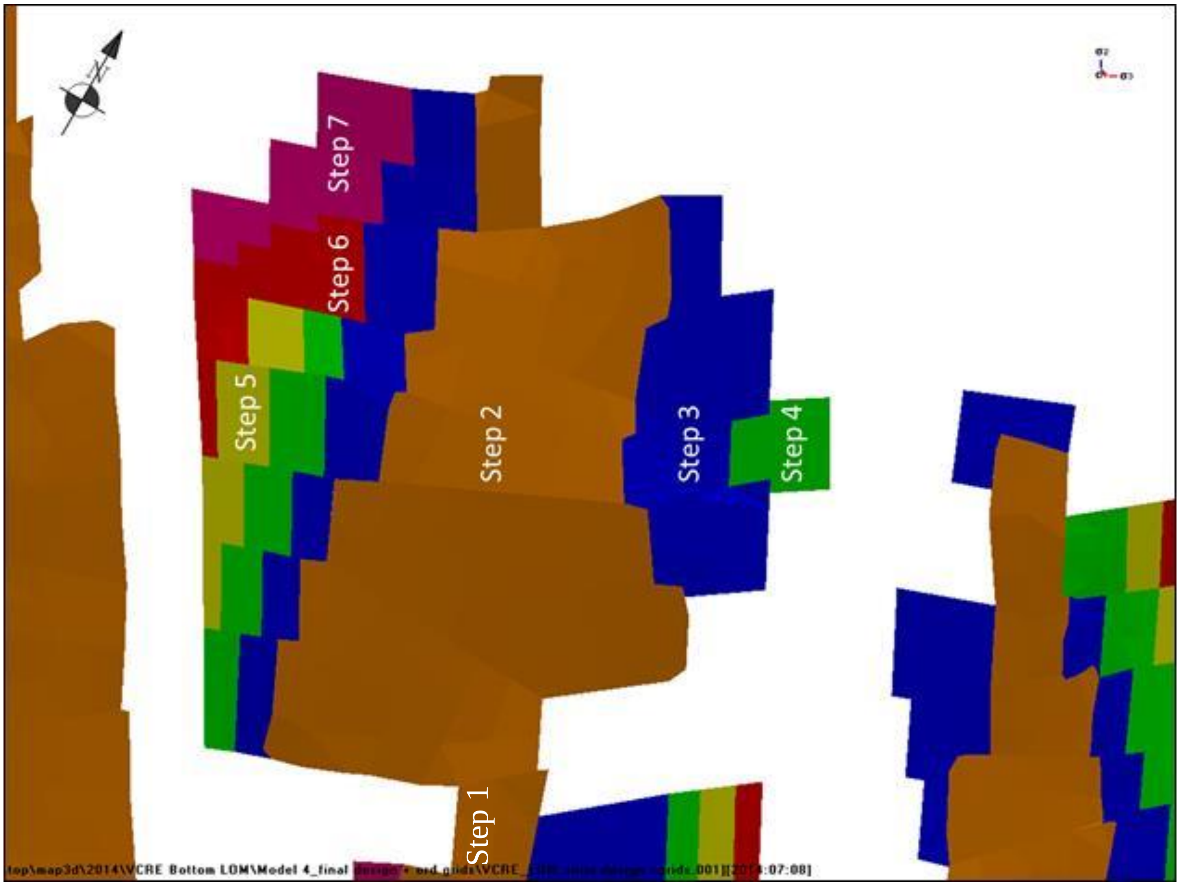


Figure 3-2: Sequence of mining a panel in a sequential grid mining layout (Mine X, 2016f)

Mine Y currently exploits the CLR using predominantly longwall mining method (Murphy, 2012; 2002). However, in recent years, a shift has been made towards sequential grid mining in order to minimise seismicity (Mine Y, 2015; Murphy, 2012). Ore extraction takes place at depths ranging between 1.8 km and 3.5 km below surface. Operations are accessed through a three-vertical-shaft system; a main shaft, secondary shaft and tertiary shaft, both the secondary and tertiary shafts are subterranean.

Figure 3-3 shows a longwall mining layout at the mine. The method is practised for maximum possible extraction. Stabilising pillars, indicated in grey are left to provide regional support.

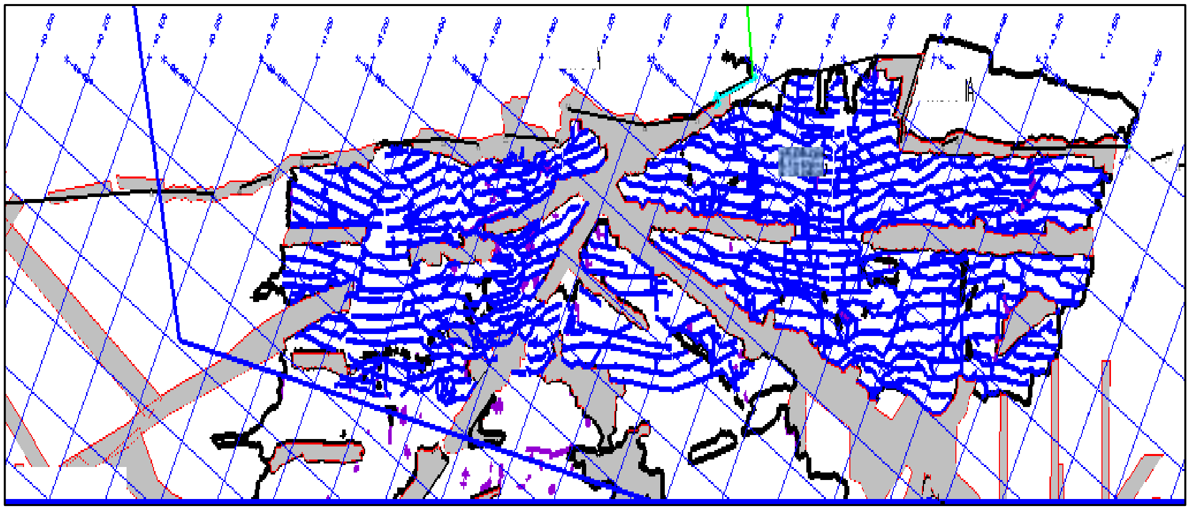


Figure 3-3: A typical longwall mining layout

3.1.2 Case studies

Fifty-two rockburst investigation reports were collected from the two mines. The readily accessible data span from 2004 to 2016. The reports outlined the damaged support elements, the recommended support elements, whether the access should be reopened by rehabilitation or by developing a new access, and the geology (host rock) and geological structures present at, or near the rockburst location.

Table 3-1 presents the rockburst data collected on site. In the 52 rockburst case studies, 22 rockbursts were in shale, 27 in quartzite and 3 in lava host rock. The rockbursts were associated with dyke, fault, joint sets and/or no visible geological structures.

Table 3-1: Rockburst frequency from 2004 to 2016 from the two deep Far West Wits mines

West Wits		
	Frequency	Percentage distribution
Total number of access levels	16	
Total number of accesses in quartzite	8	50%
Total number of accesses in shale	7	44%
Total number of accesses in lava	1	6%
Total number of rockbursts in shale tunnels	22	42%
Total number of rockbursts in quartzite tunnels	27	52%
Total number of rockbursts in lava tunnels	3	6%
Number of rockbursts associated with dykes	32	58%
Number of rockbursts associated with faults	8	15%
Number of rockbursts associated with joint sets	3	5%
Number of rockbursts associated with no structure	12	22%

Figure 3-4 shows seismic events that were experienced at Mine Y between 2012 and September 2016. It shows that over the last five years, less than 4% of seismic events recorded in a year will result in a rockburst in an access tunnel.

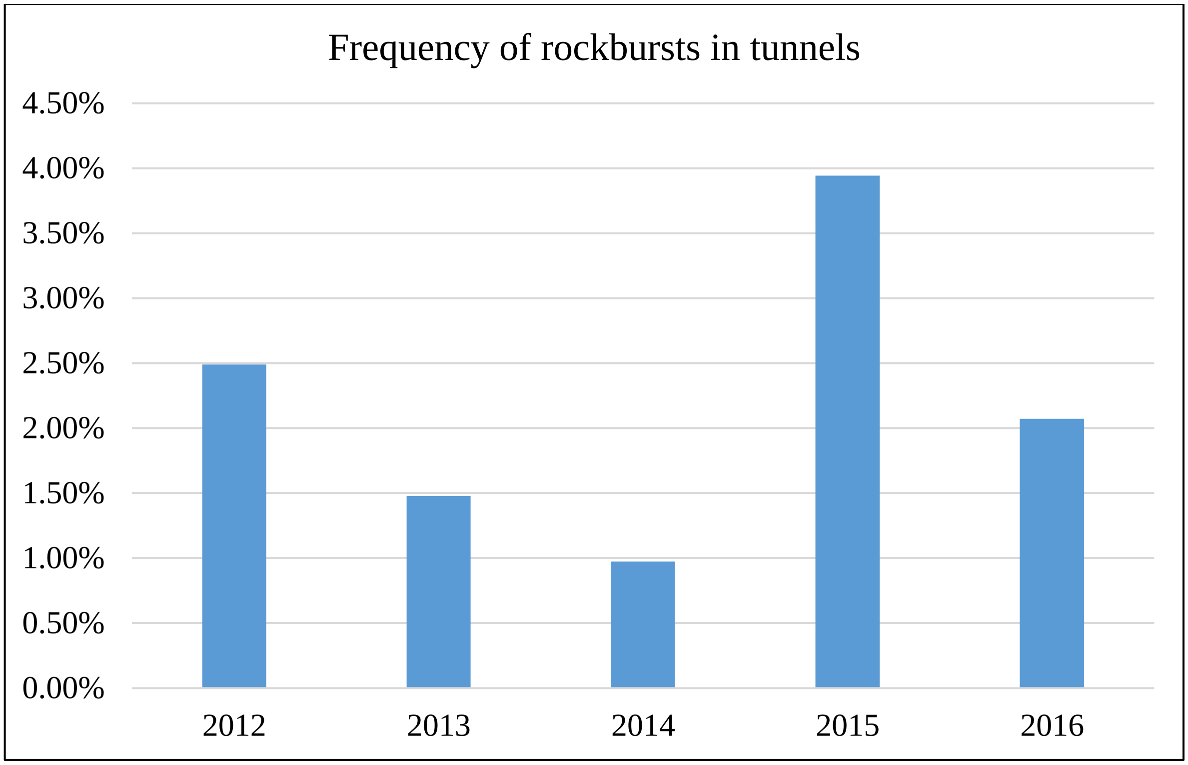


Figure 3-4: Seismic events that resulted in rockbursts in access tunnels at Mine Y

The database of the fifty-two case studies is attached in the Appendix, thirteen case studies were chosen for further analysis, of which four are analysed in detail in Chapter 4. The four rockburst case studies were chosen from recent years, most from 2010 to 2016, as these are likely to show the most recent patterns in support practices. Rock engineering reports described these four case studies comprehensively. A case study from 2009 was included as it was the most recent case study indicating total closure, where a new access had to be developed in order to access reef. Information on the thirteen case studies is provided in Table 3-2.

Table 3-2: Overview of the thirteen case studies that experienced rockburst events.

Case study	Type	Year	Location	Geology	Damage meters	Damaged support	Injuries	Fatalities	Recommended support	Damaged support costs	Casualty cost	Production loss	Recommended support cost	Yielding support system	Yielding set support system
Case study 1	Slip type	2016	Cross cut	Lava, two dykes	32	Rigid tendons, steel fibre reinforced shotcrete	0	0	Rigid tendons, long anchors, weld mesh with lacing, I-Beam set, wooden lagging, rocprops	R 143 200.00	R -	R 5 692 500.00	R 361 700.00	R 2 375 446.50	R 6 726 333.60
Case study 2	Slip type	2015	Flat end development	Quartzite, dyke, two faults	5	Rigid tendons, long anchors, weld mesh	2	1	Yielding tendons, long anchors, weld mesh with lacing, shotcrete	R 12 864.86	R 1 914 000.00	R -	R 38 594.59	R 37 705.50	R 106 767.20
Case study 3	Slip type	2009	Cross cut	Quartzite, three dykes	41	Rigid tendons, shotcrete	0	0	Yielding tendons, long anchors, mesh with lacing	R 109 500.00	R -	R 5 692 500.00	R 652 409.33	R 316 726.20	R 896 844.48
Case study 4	Slip type	2013	Travelling way	Lava, dyke, two joint sets	8	Elongates, laggings, rigid tendons	0	0	Abandoned	R 33 100.00	R -	R 1 897 500.00	R -	R 60 328.80	R 170 827.52
Case study 5	Crush type	2015	Flat end development	Quartzite, dyke	17.8	Rigid tendons, weld mesh. mechanical long anchors	0	0	Weld mesh with lacing, yielding tendons, mechanical long anchors	R 23 751.86	R -	R -	R 38 165.27	R 38 681.21	R 373 800.00
Case study 6	Slip type	2015	Flat end development	Shale, dyke	1.4	Rigid tendons, long anchors, weld mesh	1	0	Yielding tendons, long anchors, Rings sets	R 9 790.96	R 212 000.00	R -	R 80 102.29	R 10 640.00	R 203 250.14
Case study 7	Slip type	2015	Travelling way	Dyke, two faults	7	Yielding tendons, weld mesh, matpacks, elongates, I-Beam set	0	0	Weld mesh, elongates, roofbolts	R 75 117.76	R -	R -	R 30 141.93	R 23 966.87	R 147 000.00
Case study 8	Slip type	2015	Cross cut	Dyke	15	Weld mesh, yielding tendons, long anchors, I-Beam sets with voidfill	0	0	Ring sets	R 67 313.11	R -	R 1 897 500.00	R 314 907.37	R 114 000.00	R 314 907.37
Case study 9	Slip type	2015	Cross cut	Dyke	5.7	Weld mesh, yielding tendons, long anchors and shotcrete	0	0	Yielding tendons, end anchored mechanical long anchors	R 44 289.11	R -	R -	R 21 801.37	R 30 562.08	R 119 700.00
Case study 10	Slip type	2015	Haulage	Dyke	5	Rigid tendons, weld mesh with lacing, long anchors	2	1	Weld mesh with lacing, yielding tendons, long anchors	R 12 569.36	R 1 914 000.00	R -	R 28 978.88	R 42 851.07	R 105 000.00
Case study 11	Slip type	2013	Haulage	Quartzite, fault, dyke	23	Rigid tendons, chain-link mesh, long anchors	0	0	Rockprops 1 m apart on damaged sidewall with voidfill	R 30 381.86	R -	R 1 924 000.00	R 159 419.01	R 174 800.00	R 451 704.54
Case study 12	Slip type	2011	Haulage	Fault zone	25	Thin spray-on liner, Yielding tendons, long anchors	1	0	Thin spray on liner, yielding tendons, mechanical long anchors and mesh with lacing	R 35 705.44	R 212 000.00	R 1 924 000.00	R 75 977.75	R 66 526.07	R 525 000.00
Case study 13	Crush type	2010	Cross cut	Shale	0.8	Rigid tendons, weld mesh, long anchors, elongates, laggings and voidfill	0	1	Rigid tendons, weld mesh, long anchors, shotcrete, elongates, laggings and voidfill	R 15 236.09	R 1 500 000.00	R -	R 62 180.63	R 79 321.55	R 16 800.00

3.1.3 Support costs and consumables

The cost of a support system is influenced by the support requirements of the tunnel and support standards of the mine. Support standards vary by intended function of the tunnel and the geology within which the tunnel is developed. Support standards on the two mines are presented in Figure 3-5 and Figure 3-6.

Figure 3-5 shows tunnel support standards for a conventionally developed tunnel at Mine X. A standard tunnel is 3.7 m high and 3.7 m wide. The tunnel can be used for transportation (tramming) and/or for ventilation. The basic support components are grouted 4.1 m long anchors; grouted 2.2 m tendons with 300 mm faceplates and weld mesh; this support system is called Type A (Mine X, 2016b). Long anchors should be 20 m away from the face before blasting and are only installed on the tunnel roof (Mine X, 2016b). There are three 4.1 m long anchors per ring, and are installed two metres apart (Mine X, 2016b; 2016d). The 2.2 m tendons are installed 1 m away from the face, with 11 tendons per ring, and with each ring starting a metre below the grade line (Mine X, 2016b). The weld mesh sheets overlap by three grids, and a 2.2 m tendon with a faceplate used to lock the sheets in place (Mine X, 2016b). When shotcrete is recommended, it is applied at a minimum thickness of 50 mm or as otherwise recommended by the Rock Engineering Department (Mine X, 2016b).

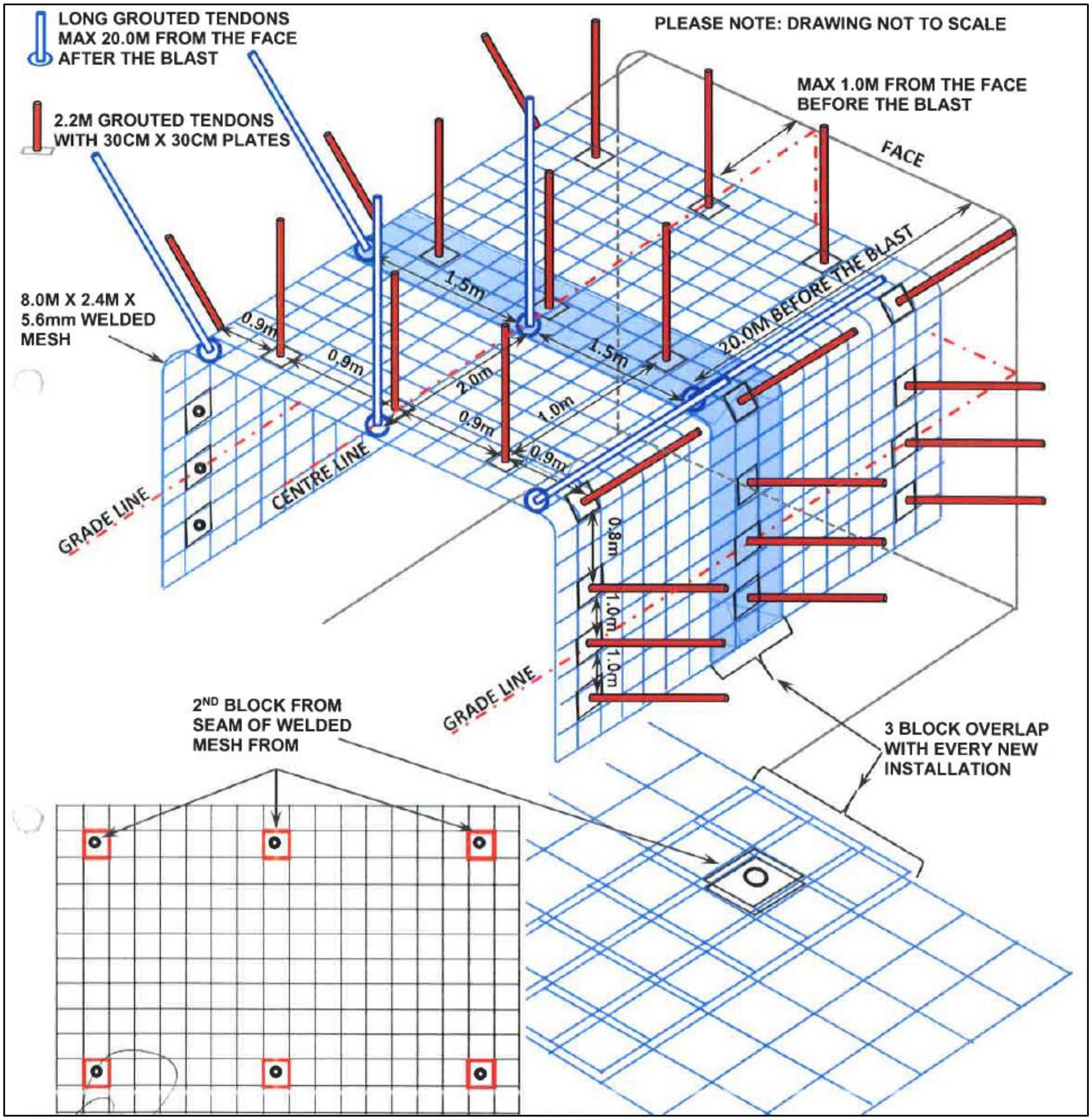


Figure 3-5: A typical conventionally developed 3.7 m x 3.7 m flat end permanent support standard (Mine X, 2016b)

Figure 3-6 shows support standards for a 3.5 m by 3.7 m access tunnel at Mine Y. This standard is for tunnels developed through possibly seismically active geological structures or where severe seismicity is anticipated. The support comprises of 4.1 m long anchors, 2.2 m yielding tendons, welded mesh with lacing, steel sets or RSJ beams with laggings and foam cement (Mine Y, 2016b). The support standard recommends nine long anchors per ring with rings spaced two metres apart, eleven yielding tendons per ring, with rings spaced a metre apart. The sets are installed 1.5 m apart with laggings and foamcrete contained by a geofabric.

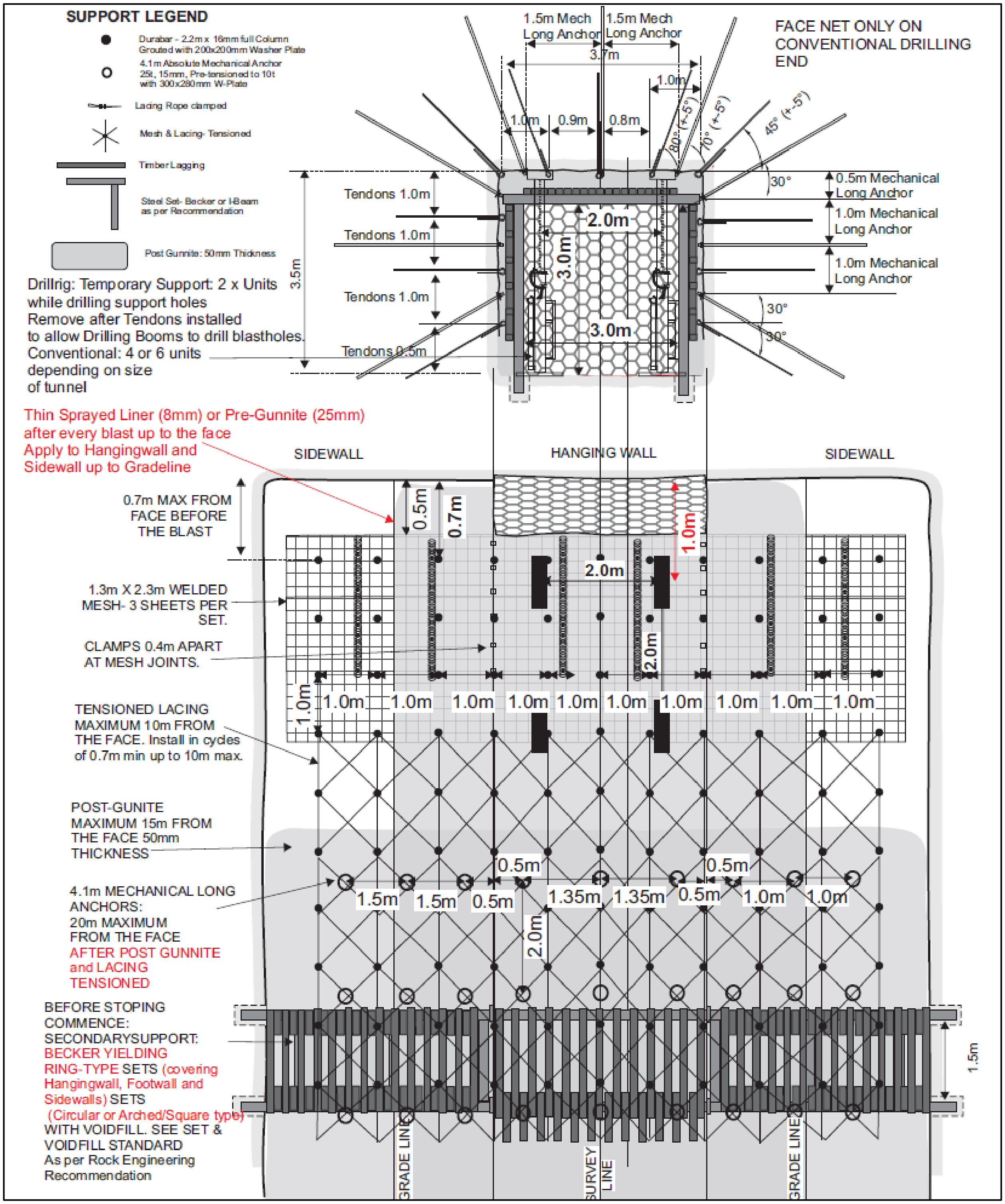


Figure 3-6: A flat end support standard of a tunnel developed through a high risk area (Mine Y, 2016b)

Support standards are fundamental in estimating costs of support systems. As stated in Chapter 2, a rigid support system comprises of rigid tendons, long anchors, weld mesh and shotcrete, while a yielding support system consists of yielding tendons with straps, long anchors, chain-link mesh with lacing and thin spray-on liner; whilst a yielding set support system consists of yielding tendons, long anchors, chain-link mesh with lacing and steel sets with void fill. An often-used yielding set substitute is the I-Beam set.

The costs of support components, explosive and other consumables were obtained from the mines' Finance Department and material catalogues. The costs and the support standards were used to estimate the cost per metre advance for each support system. Table 3-3 shows the cost in Rand per metre advance in a 3.7 m high and 3.7 m wide tunnel. The costs shown are costs of explosives and other consumables per metre advance and the costs of different support systems per metre advance. This table is part of the Executive Spreadsheet's Input Sheet. An inventory of the unit cost of each support element is listed in Table 9-6 in the Appendix. The inventory is used when support system costs are calculated in the Engineer Spreadsheet and the Primary Spreadsheet.

Table 3-3: Cost per metre advance in a 3.7 m by 3.7 m tunnel

Description	**Cost per metre in a 3.7 m by 3.7 m tunnel**
Explosive and other consumables	R 780
Static support system	R 3 600
Dynamic support system	R 7 600
Yielding set support system	R 21 300
I-Beam set support system	R 7 800

Table 3-4 shows a breakdown of support cost per metre advance in a 3.7 m by 3.7 m access tunnel. The support units are installed based on both the set support standard described in Figure 3-6 and the tendon based support standard in Figure 3-5. Table 3-4 allows the user to define the desired support systems according to mine standards and support requirements.

Table 3-4: Breakdown of various support systems (adapted from Mine X, 2016e)

Static support system		
Generic name	Specific name	Cost per metre advance
Rigid bolt grouted	2.2m splitset	R 1,000.78
Long anchor grouted	4.1m absolute mechanical anchor	R 438.36
Shotcrete	55XSAV30 N/F WETCRETE 30KG 48/PALLET	R 1,407.48
Welded mesh	2.4MX100MMSQ X9.5M LG ROLL MS GALV MESH	R 657.98
Binder Spiral	1M X 5.6MM GALVANISED WELDED MESH SPIRAL	R 82.46
		R 3,587.06
Dynamic support system		
Generic name	Specific name	Cost per metre advance
Yielding bolt grouted	2.2m Durabar+Top hat+200mm washer	R 1,098.46
Tendon straps	Square durastrap	R 4,664.19
Long anchor grouted	4.1m absolute mechanical anchor	R 438.36
Chain-link mesh	100X2400X4MMX15M COMPACTED DIAMOND MESH	R 238.21
Lacing	15 -20MMX30M SPLIT LACING ROPE EX AGA	R 28.88
Thin spray-on liner	25KG TUNNELGUARD THIN SPRAY SKIN LINER	R 1,101.87
		R 7,569.98
Yielding set support system		
Generic name	Specific name	Cost per metre advance
Yielding bolt grouted	2.2m Durabar+Top hat+200mm washer	R 1,098.46
Long anchor grouted	4.1m absolute mechanical anchor	R 438.36
Chain-link mesh	100X2400X4MMX15M COMPACTED DIAMOND MESH	R 238.21
Lacing	15 -20MMX30M SPLIT LACING ROPE EX AGA	R 28.88
Ring set	Becker ring set R1Y3500	R 17,749.80
Geo fabric	7X35M SP250 2/2 TWILL BACKFILL BULK BAG	R 158.38
Foamcrete	XP500 FOAMCRETE 50X25KG BAGS/BULK BAG	R 1,641.35
		R 21,353.44
I-Beam set support system		
Generic name	Specific name	Cost per metre advance
Rigid bolt grouted	2.2m splitset	R 1,000.78
Long anchor grouted	4.1m absolute mechanical anchor	R 438.36
Welded mesh	2.4MX100MMSQ X9.5M LG ROLL MS GALV MESH	R 657.98
I-Beams	8X35M SP250 2/2 TWILL BACKFILL BULK BAG	R 158.37
Rocprops elongates	PROP: ROC: 2.4M TO 3.5M:PURPLE: RP3520	R 1,998.01
Pipe set	6MX80MM NB SCH40 SS 316L SEAMLESS PIPE	R 940.00
Lagging	PLATE:FP1001;FOOT;5 MM:ROCPROP	R 802.48
Geo fabric	7X35M SP250 2/2 TWILL BACKFILL BULK BAG	R 158.38
Foamcrete	XP500 FOAMCRETE 50X25KG BAGS/BULK BAG	R 1,641.35
		R 7,795.71

For the purpose of this research, explosives and their associated consumables are only considered during development of a new access tunnel as a remedial course of action after a rockburst damage. Underground waterproof bulk explosives are used. It is assumed that the detonators have a long enough shock tube to connect adjacent blast holes. Table 3-5 shows a breakdown of components that make up consumables.

Table 3-5: Explosives and consumable costs per metre advance (adapted from Mine X, 2016g)

Explosives		
Generic name	Specific name	Cost per metre advance
Bulk explosive	Sasol DDS Base Emulsion PN 16067 Bulk	R 80.12
Sensitizer	Sasol DDS Sensitiser Emulsion 25l/Drum	R 3.73
Detonator	IED Detonator System 1.8m 100/Case	R 278.80
Tamping	25mmx240mm Tamping Capsule AGA 247/001	R 414.00
		R 776.65

3.1.4 Personnel casualty

According to the Compensation for Occupational Injuries and Diseases Act (COIDA), if an employee sustains a casualty while at the workplace, they or their kin are entitled to a compensation. The compensation is calculated based on the extent of the casualty and the normal wages of the personnel (Rwodzi, 2011). In this dissertation, it is assumed that all personnel that incurred injuries are compensated. A lost time injury is when the injured person was hospitalised for 14 days or less and a serious injury is when the injured person was hospitalised for more than 14 days and/or is permanently disabled. Table 3-6 shows the average medical and compensation costs of a work place casualty.

Table 3-6: Average medical and compensation costs of workplace casualties

	Cost per casualty
Lost Time Injury	R 2 000.00
Serious Injury	R 12 000.00
Compensation: Injury	R 200 000.00
Compensation: Fatality	R 1 500 000.00

3.1.5 Revenue loss

A blocked tunnel can interrupt movement of ore from the stope raise line to the shaft. The following assumptions were made regarding the production raise lines connected to affected access tunnels.

- There are three production crews working in a raise line at any given time
- Each crew has a 400 t monthly target, therefore a 100 t weekly target
- The gold grade is 10 g/t
- The operation has a built-in flexibility
- The average for moving out of an affected panel and establishing a new panel is three weeks
- The effective gold price (regardless of year of rockburst) is R 575 000, 00/kg. The price is derived from the gold prices in 2016 as shown in Figure 3-7. This enabled the evaluation of costs as near net present value as possible.

Figure 3-7: Gold price in R/kg over the last year (GoldPrice, 2017)

3.1.6 Equations

The Excel model uses formulae to calculate the consequences of rockbursts. The equations used are described below.

Labour cost

The following equations are used to estimate the cost of labour. Mine crew costs describes the wages of the mine employees. These costs are to be disregarded, as labour costs are considered overhead cost. The contractor costs (both the mesh and lacing, and set contractors) are additional costs to the operation.

$$Labour\ cost = Mesh\ and\ Lacing\ contractor\ costs + Set\ contractor\ costs + mine\ crew\ costs \quad 3.1$$

$$Mesh\ and\ Lacing\ contractor\ costs = cost\ per\ linear\ metre \times linear\ metres \quad 3.2$$

$$Set\ contractor\ costs = cost\ per\ metre \times linear\ metres \quad 3.3$$

$$Mine\ crew\ costs = cost\ per\ metre\ \times linear\ metres \qquad 3.4$$

$$= duration\ (in\ months)\ \times monthly\ wages$$

Where linear metres refer to either the original damage linear metres or remedial (i.e. rehabilitation or new access) linear metres.

<u>Personnel casualties</u>

These are costs associated with medical costs of injured personnel, and their compensation and compensation of their family in the event of death.

$$Casualty\ cost = \ lost\ time\ injuries\ costs + serious\ injuries\ costs + injury\ compensation + fatality\ compensation \qquad 3.5$$

$$Lost\ time\ injury\ cost = number\ of\ personel\ \times\ lost\ time\ injury\ medical\ costs \qquad 3.6$$

$$Serious\ injury\ cost = number\ of\ personel\ \times\ serious\ injury\ medical\ costs \qquad 3.7$$

$$Injury\ compensation = \ number\ of\ cases\ \times average\ injury\ compensation\ per\ case \qquad 3.8$$

$$Fatality\ compensation = number\ of\ fatalities\ \times average\ compensation\ per\ fatal \qquad 3.9$$

<u>Explosives</u>

These are costs of explosives and their associated consumables, used during blasting. Packaged explosives are explosives in small portable cartridges while bulk explosives have two components, the base and the sensitiser. The mixture of the base and sensitiser is pumped into the drilled holes. It is assumed that the detonator has an attached shock-tube, which is long enough to connect to the neighbouring blast hole.

$$Bulk\ explosive\ cost = \ explosive\ base\ costs + sensitiser\ costs + detonator\ costs + tampingcosts \qquad 3.10$$

$$Packaged\ explosive\ cost = cartridges\ costs + booster\ costs + sensitizer\ costs + detonator\ costs + tamping\ costs \quad 3.11$$

$$Bulk\ explosive\ base\ cost = number\ of\ blast\ holes \times volume\ of\ hole \times density\ of\ explosive\ base \times percentage\ explosive\ base \times {}^{Unit\ cost}/_{weight\ of\ unit} \quad 3.12$$

$$Bulk\ explosive\ sensitiser\ cost = number\ of\ blast\ holes \times volume\ of\ hole \times density\ of\ sensitiser \times percentage\ sensitiser \times {}^{Unit\ cost}/_{weight\ of\ unit} \quad 3.13$$

$$Detonator\ cost = number\ of\ holes \times unit\ price \quad 3.14$$

$$Tamping\ cost = number\ of\ holes \times unit\ price \quad 3.15$$

$$Cartridge\ cost = number\ of\ holes \times units\ of\ cartridges\ per\ hole \times cartridge\ unit\ price \quad 3.16$$

$$Booster\ cost = number\ of\ holes \times units\ per\ hole \times unit\ price \quad 3.17$$

<u>Tendons</u>

These are costs associated with supporting given metres with tendons, either rigid, yielding or long tendons. The cost are estimated per ring and are then extrapolated over the given linear metres using the inter-row spacing of the rings. The number of tendons required per ring are estimated based on the support standards of the mine or calculated using work of Ortlepp (1994) and Ortlepp & Stacey (1995), discussed in Chapter 5; where the tendon spacing is:

$$\text{Tendon spacing} = \sqrt{\frac{Peak\ load\ of\ tendon}{Required\ force}} \qquad 3.18$$

$$Tendon\ support\ cost = tendon\ costs + face\ plate\ costs + grout\ costs \qquad 3.19$$

$$Tendon\ cost = number\ per\ ring \times \frac{linear\ metres}{inter{-}row\ spacing} \times unit\ cost \qquad 3.20$$

$$Face\ plate\ cost = number\ per\ ring \times \frac{linear\ metres}{inter{-}row\ spacing} \times unit\ cost \qquad 3.21$$

$$Grout\ cost = number\ of\ holes\ \times (volume\ of\ single\ hole - volume\ of\ tendon) \times density\ of\ grout \times unit\ cost \qquad 3.22$$

Sets

The cost of a steel set support system consists of the costs of steel sets, lagging (if required), geofabric and foamcrete.

$$Set\ cost = \ set\ costs + laggings\ costs + geofabric\ costs + foamcrete\ costs \qquad 3.23$$

Set: either manufacturer steel sets or I-Beam sets

$$Steel\ sets\ cost = \left({}^{linear\ metres}/_{Set\ spacing} + 1\right) \times unit\ cost \qquad 3.24$$

$$I - Beam\ set\ cost\ = (number\ of\ beams\ in\ a\ ring \times unit\ cost) \times \left({}^{linear\ metres}/_{inter - row\ spacing} + 1\right) \qquad 3.25$$

$$Lagging\ cost\ = \left({}^{linear\ metre}/_{length\ of\ lagging}\right) \times number\ of\ laggings\ in\ a\ ring\ \times unit\ cost \qquad 3.26$$

$$Geofabric\ cost\ = \left({}^{linear\ metres}\!/_{length\ of\ geofabric}\right) \times number\ of\ geofabric\ in\ a\ ring \times unit\ cost \qquad 3.27$$

$$Foamcrete\ cost = (cross\ sectional\ area\ of\ tunnel - cross\ sectional\ area\ of\ set) \times linear\ metres \times foamcrete\ density \times percentage\ solid \times {}^{unit\ cost}\!/_{unit\ weight} \qquad 3.28$$

Skin support

Skin support cost refers to cost associated with shotcrete and thin spray-on liner. The units of measure are metric.

$$Shotcrete\ cost\ = affected\ area \times application\ thickness \times shotcrete\ density \times {}^{unit\ cost}\!/_{unit\ weight} \qquad 3.29$$

$$Thin\ spray - on\ liner\ cost = affected\ area \times application\ thickness \times thin\ spray - on\ liner\ density \times {}^{unit\ cost}\!/_{unit\ weight} \qquad 3.30$$

Areal support

$$Costs =\ mesh\ costs + lacing\ costs \qquad 3.31$$

$$Mesh\ costs = affected\ area \times \frac{Linear\ metres}{unit\ lenth} \times number\ of\ sheets \times \frac{unit\ cost}{unit\ dimensions} \qquad 3.32$$

$$Lacing\ cost = \left[\left(1 + \frac{Width}{a}\right) \times \frac{linear\ metres}{b} + \left(1 + \frac{linear\ metres}{b}\right) \times \frac{tunnel\ width}{a}\right] \times unit\ cost/area \qquad 3.33$$

Where a and b are dimensions of the lacing pattern

Production loss

Production lost is associated with delay of production as a crew is changing from one working place to the other.

$$Revenue\ loss = average\ ore\ tonnage\ per\ week \times average\ grade \times number\ of\ crews \times duration\ of\ crew\ standing\ time \times gold\ price \qquad 3.34$$

Conversion ratios

$$Support\ conversion = \frac{2 \times height + width}{3.7 + 3.7 + 3.7} \qquad 3.35$$

Equation 3.35 is used for support where perimeter has to be considered.

$$Development\ conversion = \frac{height \times width}{3.7 \times 3.7} \qquad 3.36$$

Equation 3.36 is used for development where cross sectional area must be considered

To determine the magnitude of the loss associated with the rockbursts, the following calculations need to be made. The expected financial loss is the sum of all indirect financial consequences. The cost of the rockburst is all the financial losses incurred due to the rockburst, this includes the value of the initial investment into the tunnel before the rockburst. Value is the amount of loss that could have been prevented if an appropriate support (energy absorbing support system in this case) was in place.

Expected financial loss = Production loss + resupporting costs + casualty costs 3.37

Total cost of rockburst = Expected loss + original support costs 3.38

Value = Total cost of rockburst – cost of dynamic support 3.39

3.2 Formulation of the Model

The Consequence-Quantifying model is the main product of this research. The consequence-quantifying model uses consequences described in Chapter 2 and the material catalogue to estimate the cost of rockburst damage in each case study. The model has three versions, each suited for a specific function. The model is applied to rockburst case studies in order to evaluate the financial impact.

3.3 Consequence quantifying model

Consequence is one of the components of risk, the other being probability of occurrence. This research focuses on quantifying the indirect financial consequences of rockbursts. The consequences quantified include costs of support elements, financial implications of personnel casualties and lost revenue due to interruption of production. The model has three versions, each adapted for specific function. The three versions of the model are discussed below. The following are assumptions made when developing the model. These assumptions can be modified to suit the user's preferences and different mine standards.

- A 1 m advance during development
- There are 11 tendons per ring and the rings are spaced 1 m apart
- There are 3 long anchors in a ring and the rings are spaced 2 m apart
- Long anchors are only installed in the tunnel roof
- Face blast holes are 60 cm apart, and thus there are 18 blast holes including a five-hole burn cut

3.3.1 Executive Spreadsheet

The Executive spreadsheet is a simplified and least detailed of all the versions of the model. It provides a concise overview of consequences of rockburst and the support requirements. The spreadsheet uses support systems defined in Chapter 2, and material catalogues to estimate the cost of the support system under conditions given in the case studies. There are four support systems, namely rigid support, yielding support, yielding set support and I-Beam set support.

The executive spreadsheet is made up of three Excel sheets, the input sheet, the costs sheet and the support sheet. The details of these sheets are discussed in Section 3.4.

3.3.2 Engineer Spreadsheet

This version of the model allows the engineer to tailor the support to the tunnel support requirements and to evaluate a financially optimum support system. The user chooses the support elements that make up the support system. This spreadsheet assumes that all the support units are installed identically on all walls of the tunnel, and that the support units are installed according to mine support standards. The version has two sheets, namely the input and the inventory sheets.

3.3.3 Primary Spreadsheet

The primary spreadsheet of the model facilitates back-analysis and it is arguably the most precise and detailed of the three spreadsheets. The spreadsheet considers support installation practices as they are at the location of the rockburst and does not assume that all walls of the tunnel are supported identically nor that the support was installed to standard. When quantifying damage costs, this spreadsheet considers the actual damaged area, the actual number of tendons in a ring and only the affected walls, as opposed to the other spreadsheets that assume that the tendons were installed uniformly and to standard throughout the tunnel. This spreadsheet has two sheets, the input sheet and the support sheet.

3.4 Structure of the Model

3.4.1 Input sheet

The input sheet is the interface through which the user interacts with the model. All the different spreadsheets of the model have the input sheet. The input interfaces of all the spreadsheets are similar, except that in the primary and engineer spreadsheets, the users choose support components to tailor the support systems while with the executive spreadsheet, the user chooses a support system from predefined options.

The input sheet has four columns: the first column (Column A) describes the item that is to be inserted into the sheet. Column B: labelled “units” gives a brief description of the unit of measure of items described in Column A. In some cells, Column B gives a short instruction as to what the user should do when interacting with Column C. Column C labelled “data input” is an array of cells with which the users interact and are colour coded in green to differentiate them from the other columns. In “data input”, alphabetic entries are chosen from a drop-down list while the user types in numeric entries.

The input sheet is further divided into five major divisions across. The divisions are damage description, personnel casualties, original support, loss of revenue and remedial course of action.

Damage description describes the dimensions of the damage in terms of linear metres of damage, original tunnel height and tunnel width. Personnel casualties describe the injuries or fatalities incurred due to rockbursts. Original support system describes the support components that were present at the location during the rockburst event. Loss of revenue describes the revenue lost due to interrupted ore flow. For the remedial course of action, the user picks, from a drop-down menu whether the damage area was abandoned, rehabilitated or has a new access developed. In cases where the access is not abandoned, the user will state the linear metres of rehabilitation or of new access development.

3.4.2 Cost sheet

The cost sheet feeds support and labour costs into the input sheet. The costs are defined in Table 3-3 to 3-6. Support and explosive costs are estimated in Rands per metre advance in a 3.7 m wide and 3.7 m high access tunnel. Should the tunnel dimensions in a given case study differ from these dimensions, the conversion ratios described in Section 3.1.6 are used to reduce discrepancies.

3.4.3 Inventory sheet

The Oxford English dictionary (2016) defines inventory as a complete list of items. The inventory sheet has a collection of all the available material, support or otherwise that, for the purposes of this research may be necessary to estimate the costs associated with rockbursts. Table 9-6 in the Appendix is an inventory of support and other material items on the vendor catalogue. Unit costs of the items were converted into cost per metre advance using mine support standards and development standards, as shown in Figure 3-5 and Figure 3-6. The tunnel in this inventory is assumed to be 3.7 m high and 3.7 m wide. Each inventory sheet can be customised for each mine according to the mine's standards. The primary and engineer spreadsheets use the inventory sheet to estimate costs while the executive spreadsheet uses the cost sheet to estimate costs.

3.4.4 Support sheet

In the primary spreadsheet, the user constructs a support system based on the support components as observed underground and described in rock engineering reports. This sheet is divided into two major sections, namely damage description and remedial action. These two major sections are further divided into groups by the types of support. In each case study, the user inputs the number of support units (e.g. tendons), the actual skin support thickness and affected area as observed at the damage location. When calculating remedial action costs, the user may assume that the support units are to be installed to standard or as recommended. The inventory shown in Table 9-6 in the Appendix has material unis costs in Column 9. When choosing support units to build a system, the user will pick names of support units from a dropdown menu. Using the chosen support unit, a vertical look up will pull out the unit cost of the material from Column 9.

3.5 Summary

In this chapter, the information collected from the case study mines was described. The information collected include the geology and support systems or components at the location of the rockbursts, the number of injured personnel, material and medical costs. The information was used to formulate an Excel model to quantifying rockburst consequences. The Excel model was named Consequence-quantifying model and has three versions, namely, the primary, the engineer and executive spreadsheets. The spreadsheets have the input sheet in common, which is the interface with which the user interacts.

4 CHAPTER 4: APPLICATION OF THE MODEL

In this chapter, the consequence-quantifying model described in Chapter 3 is applied to four case studies. The case studies are:

- A benchmark case study,
- a new access case study,
- a rehabilitation case and
- an abandoned access case study.

Each case study will be evaluated with the three different spreadsheets of the model. The results from each spreadsheet are analysed individually and comparatively per case study.

4.1 Case Study 1: Benchmark Case Study

The purpose of the benchmark case study is to establish which of the spreadsheets is reliable under which conditions. The case study was evaluated at the mine with the help of mine employees, who participated in the remediation of this access.

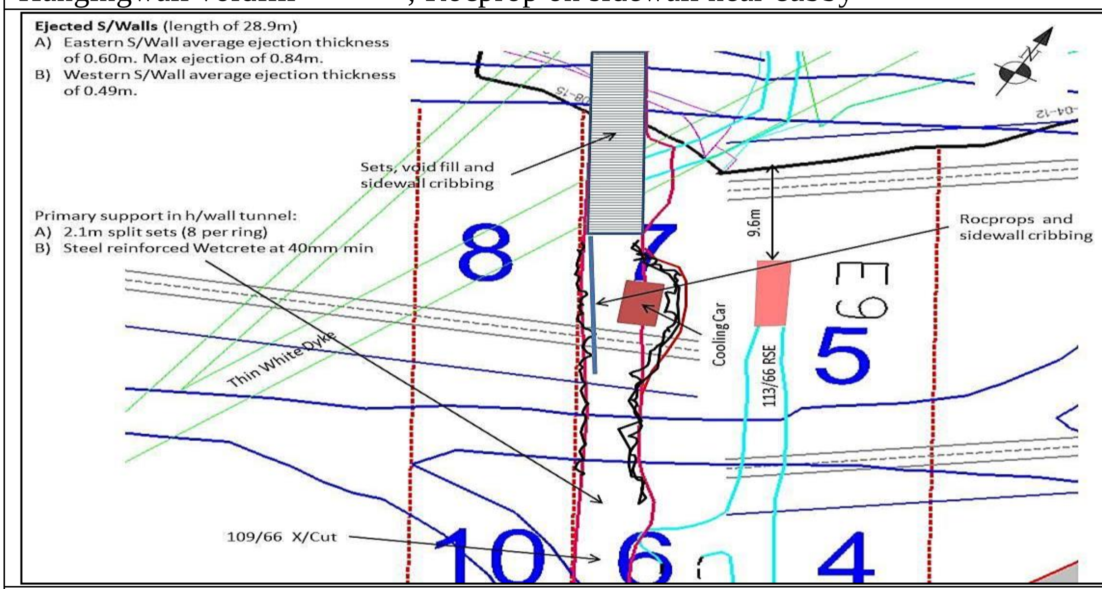
4.1.1 Background

The benchmark case study is a rehabilitation case study from Mine X. A seismic slip type event of 0.4 local magnitude (M_L) occurred at the mine in 2016 resulting in rockburst damage. The rockburst damage occurred in a crosscut tunnel at a depth of 3.3 km. The crosscut is a hangingwall drive developed in strong lava with uniaxial compressive strength ranging between 250 and 300 MPa. Two dykes, the Thin White Dyke and Disappearing Dyke were in close proximity to the damage location. The slip rockburst event occurred along the Thin White Dyke and resulted in rock ejection on both sidewalls of the crosscut tunnel. Table 4-1 summarises the background of the case study, from a seismic event investigation report (Mine X, 2016f).

The case study summarises revenue losses due to interrupted ore flow, rehabilitation support costs, damaged support costs and cost of consumables. The main purpose of this case study is to determine which of the spreadsheets will replicate the total financial loss estimate at the mine.

Table 4-1: Description of case study 1: Base case adapted from (Mine X, 2016f)

Case study 1	
Description of accident	
Tunnel height: 3.7 m	Tunnel width: 3.7 m
Damage: Both sidewalls Line metres : 25 on W sw and 31.9 on E sw Volume : 144.47 m^3 Area : 212 m^2	Number of Casualties Lost Time Injuries : 0 Serious Injuries : 0 Fatality : 0
Type of event : Slip failure (rockburst)	Seismic event magnitude : 0.4 M_L
Geological features in the vicinity: Hanging wall drive near reef intersection; Lava, near Disappearing and Thin White Dykes	
Name of support material	
Tendons 2.1m splitset, eight per ring ; Steel-fibre reinforced wetcrete >40mm Pipe sets & RSJ beam ; Hangingwall and side wall laggings Hangingwall voidfill ; Rocprop on sidewall near cubby	



Rock engineering recommendations
Course of action : Rehabilitate the access
Line metres : 42 m Duration : 3 months
Name of support material
Ten 2.1 m Splitsets per ring at 1 m interring spacing 4.5 m Koepe rope (Long anchors) ; Mesh and lacing RSJ beams ; Wooden laggings ; Rocprops

The portion of the tunnel that failed was supported only with primary support. The primary support comprised of 2.1 m splitsets and steel-fibre reinforced shotcrete. While the part of the tunnel support with I-Beam sets did not experience damage. The picture on the left in Figure 4-1A shows RSJ support across from across the cooling car in cubby, the sidewall behind the cooling car had extensive rockburst damage as shown in Figure 4-1A and B. Figure 4-1C shows damage on both sidewalls in the crosscut. Figure 4-1D shows damage near the reef intersection.

Figure 4-1: Pictures of rockburst damage. (Mine X, 2016f)

It was recommended that the access tunnel be rehabilitated. The cross cut and the reef intersection were to be cleaned and re-supported. The support used during rehabilitation included permanent support of rocprop elongates at 1.5 m spacing and 1 m away from the sidewall with timber laggings installed to secure the sidewalls. The void between the sidewall and laggings was filled with foamcrete.

Figure 4-2A and B show support installed along the cross cut as recommended. In Figure 4-2C, the hangingwall was supported with an additional chain-link mesh attached to the roof with shepherd crooks and laced on a 1.5 m diamond pattern. The reef intersection was closed off as shown in Figure 4-2D.

Figure 4-2: Pictures of the rehabilitated crosscut (Mine X, 2016f)

4.1.2 Case study results

The background information in Table 4-1 were input into the different spreadsheets of the consequence-quantifying model. The input interfaces from the executive, engineer and primary spreadsheets, are in the Appendix in Table 9-2, Table 9-7 and Table 9-11 respectively. The results are presented in this section and are later discussed in the case study summary. The analysis is made by comparing the estimated costs from the different model spreadsheets against cost estimates made with the help of the mine staff. Figure 4-3, Figure 4-4 and Figure 4-5 are presented to show the accuracy of the different spreadsheets. This will help determine which spreadsheet is applicable under which conditions.

Executive spreadsheet results

Financial losses are associated with indirect consequences of rockburst damage. These losses include personnel casualty medical and compensation costs, cost of damaged support and loss of revenue due to interrupted ore flow. Remediation cost are due to the steps taken to reopen the damaged access tunnel.

Figure 4-3 shows a summary of the financial loss associated with this case study as estimated with the executive spreadsheet. The estimated revenue loss is R 5.69 million. The I-Beam support system as defined in Chapter 3, assumed that there were RSJ beams installed on both the sidewalls and the hangingwall was void filled with foamcrete. The estimated rehabilitation support cost is R 384 200. The spreadsheet calculates that it took a 21-member crew approximately two months (1.67 months) to rehabilitate the access. These numbers are summarised in Figure 4-3 and the full results are in Table 9-2 in the Appendix.

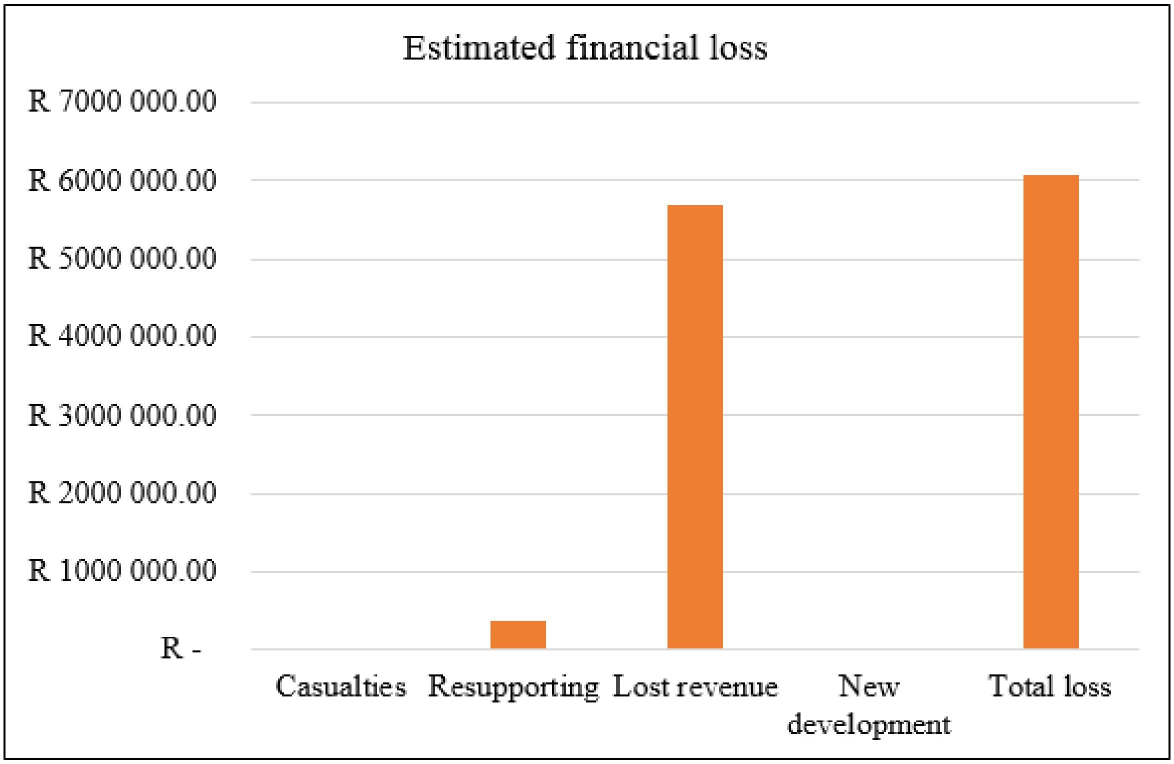


Figure 4-3: Summary of the benchmark case study using the executive spreadsheet.

Engineer spreadsheet results

This spreadsheet assumes that there were RSJ beams with laggings and voidfill installed on both the sidewalls and roof of tunnel as a rehabilitation strategy. The estimated cost of rehabilitation support is at R 391 200. It took approximately two months (1.67 months) to rehabilitate the access. The estimated revenue loss is R 5.69 million. These figures are summarised in Figure 4-4. The full results are in Table 9-7 of the Appendix.

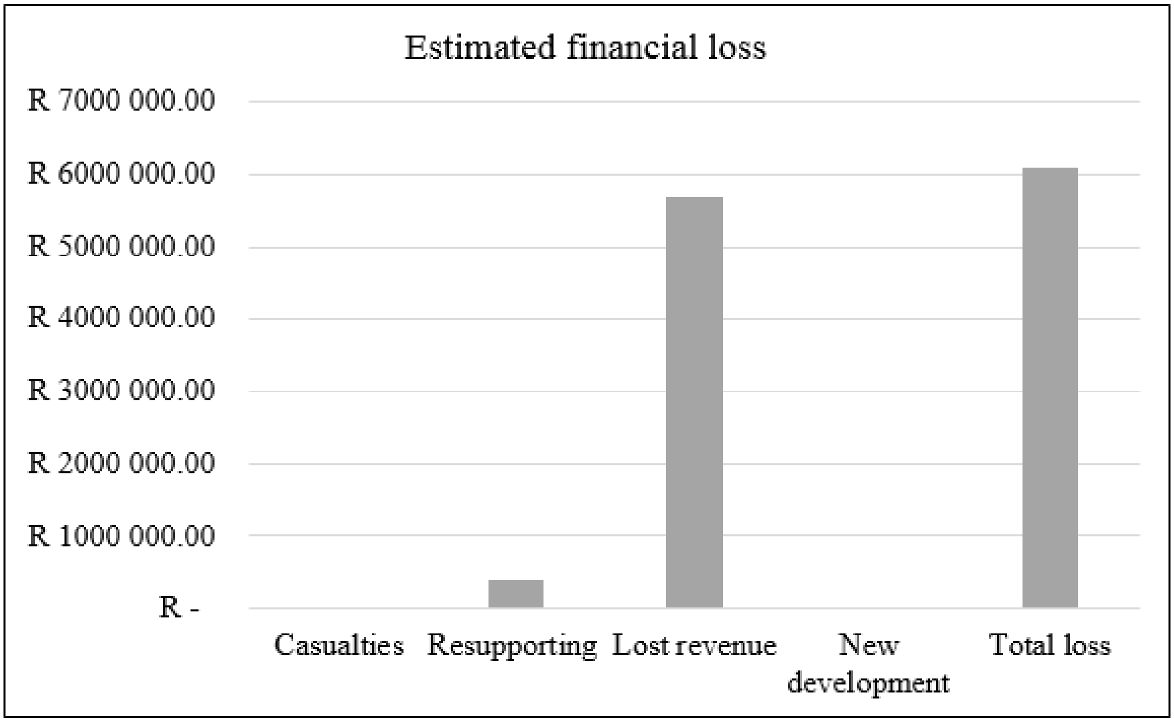


Figure 4-4: Summary of financial loss in benchmark case study using the engineer spreadsheet.

Primary spreadsheet results

The estimated cost of rehabilitation support is R 361 700. The report recommended 4.5 m long anchors while the predefined I-Beam support system uses 4.1 m long anchors as a default. The model estimates that it took a 21-member crew two months (1.67 months) to rehabilitate the access tunnel. The estimated revenue loss is R 5.69 million. These costs are summarised in Figure 4-5.

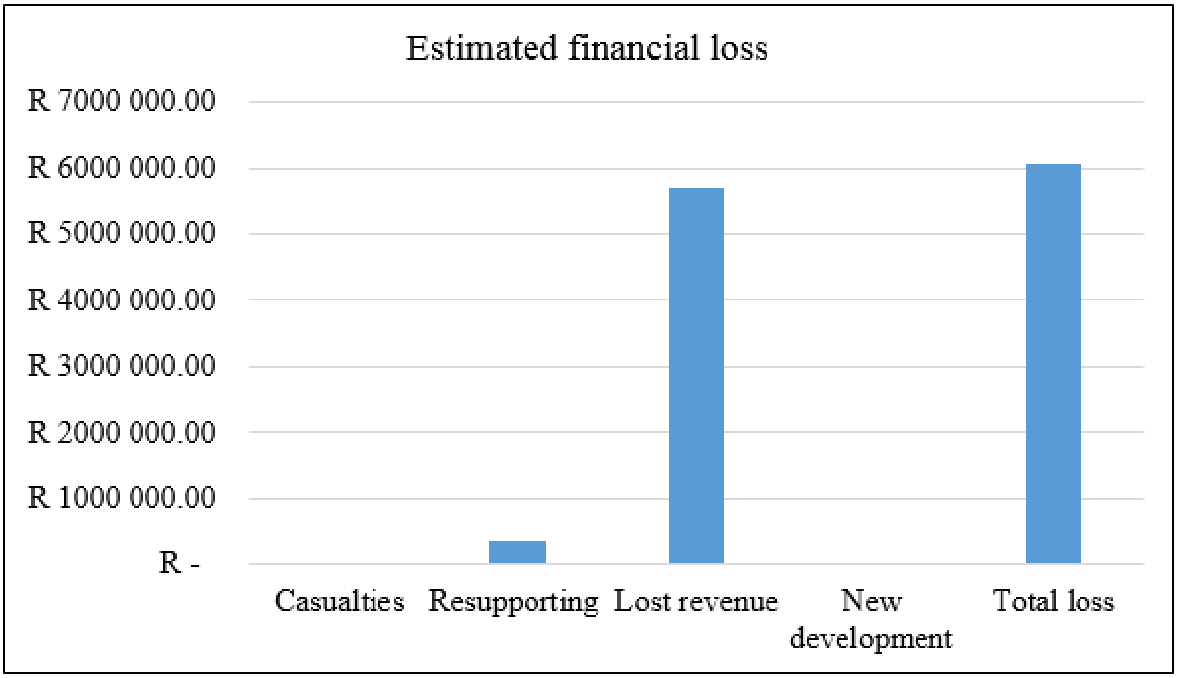


Figure 4-5: Summary of financial loss associated with the benchmark case study using the primary spreadsheet

Base calculations

The base calculations are the benchmark used to determine the accuracy of the three versions of the model. Results from each spreadsheet will be compared to base calculations in order to determine the deviation between the base calculations and results obtained with the different spreadsheets. The spreadsheet that produces results closest to the base are considered the most accurate of the three.

The production department helped estimate financial losses associated with this rockburst. The estimates were derived from known project schedule, financial documentations and experience when rehabilitating the tunnel. Table 4-2 shows the cost of rehabilitating the tunnel. Once the crosscut was declared unsafe, ore movement from the raise was interrupted (D Nethavhanani, 2016, pers.comm., 24 November). This resulted in three production crews' inability to mine the reef for three weeks while new panels are established. The raise line has an average grade of 10 g/t, with each crew having a weekly target of 110 t. This resulted in an estimated revenue loss of R 5.69 million. The cost of rehabilitation support is R 364 400. Unlike the other versions of the model, only the sidewalls were considered for the support and did not assume that all the walls of the tunnel had void-filled I-Beam support system. It took a 21-member crew three months to rehabilitate the crosscut and a labour cost of R 1 333 800 (D Nethavhanani 2016, pers.comm., 24 November). These figures are summarised in Table 4-2.

Table 4-2: Summary of rehabilitation costs of the benchmark case study as estimated with the assistance of the Mining Department.

Rehabilitation costs	
Description	Rehabilitation cost
Consumables	R 76 117,70
Rehabilitation support	R 363 479,33
Labour	R 1 333 779,00
Revenue loss	R 5 692 500,00
Total	**R 7 465 876,03**

4.1.3 Value added by support systems

Oxford Online English dictionary (2016) defines value as “the worth of something compared to the price paid for it”. Investors want to get the highest possible worth out of their investment, i.e. they want high value compared to the price paid to commission the project. A high price does not necessarily mean high value or high return on investment; neither does a low price. It is beneficial to spend sufficient funds on systems that will preserve or add value. Value is calculated as the difference between the total financial loss and the cost of support systems. The mine could have saved this amount money if a comprehensive energy absorbing support system was used to support the tunnel.

In the South African mining industry, most companies are trying to keep costs as low as possible due to the declining financial performance of the industry. This sometimes results in mines opting for the cheapest possible support in order to minimise costs. However, this may lead to destruction of value, as the cheaper support (rigid support) is not suitable for rockburst prone mining environments. Most mining companies have safety as the first value, thus a balance between support costs and support efficiency is required in order to get the highest possible value (both monetary and safety value) out of the support systems for the money paid. In rockburst prone deep level gold mines, support systems with energy absorbing capabilities are the most suitable and are likely to contain a rockburst event. This will result in preserved or improved financial value.

All the spreadsheets indicated that a financial value of R 5.96 million could have been preserved by a yielding support system at an additional cost of R 241 315 as shown in Figure 4-6. For this case, it was concluded that yielding set support system was the most suitable due to the two seismically active dykes through which the tunnel was developed. It can be assumed that if the mine had used yielding sets during development, the access wouldn't have experienced a rockburst damage and a value of R 5.51 million at a cost of R 683 310 could have been preserved.

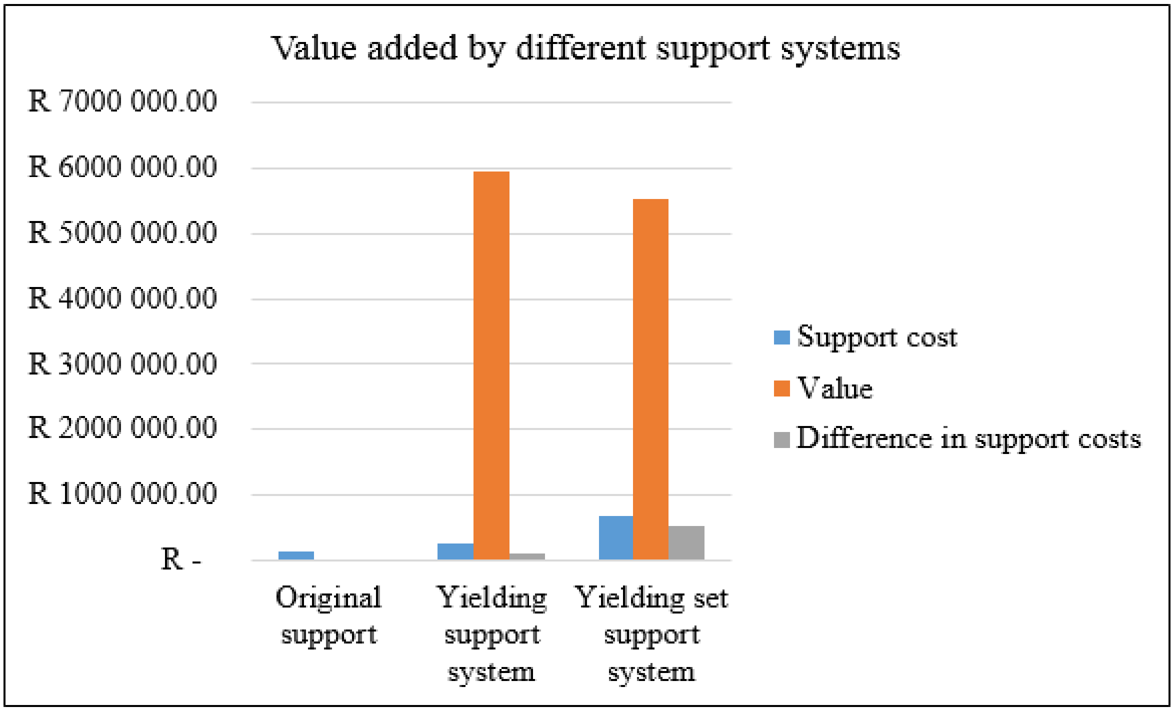


Figure 4-6: Value added by support systems to base case

4.1.4 Case study summary

In this case study, the financial loss estimated with the consequence-quantifying model is compared to the financial loss that was calculated in the base calculation. Revenue loss and rehabilitation support costs in the base calculation were estimated at the operation with the help of production and finance departments. These estimates are the closest to the actual financial loss incurred due this rockburst event.

All the spreadsheets estimated the same revenue loss. This was expected, as the assumptions made to estimate the revenue loss did not change for each spreadsheet. In all the spreadsheets, the expected advance rate is 25 m per month resulting in 1.7-month duration of rehabilitating the 42 m of the access tunnel. This advance rate does not match the 3-month actual duration of rehabilitation in the base calculations. The other source of variation is peroneal bonuses that the crew received while rehabilitated the tunnel.

Each spreadsheet shows different costs of rehabilitation support systems. In order of increasing costs of rehabilitation support: primary spreadsheet, base calculations, executive spreadsheet and engineer spreadsheet as shown in Figure 4-7.

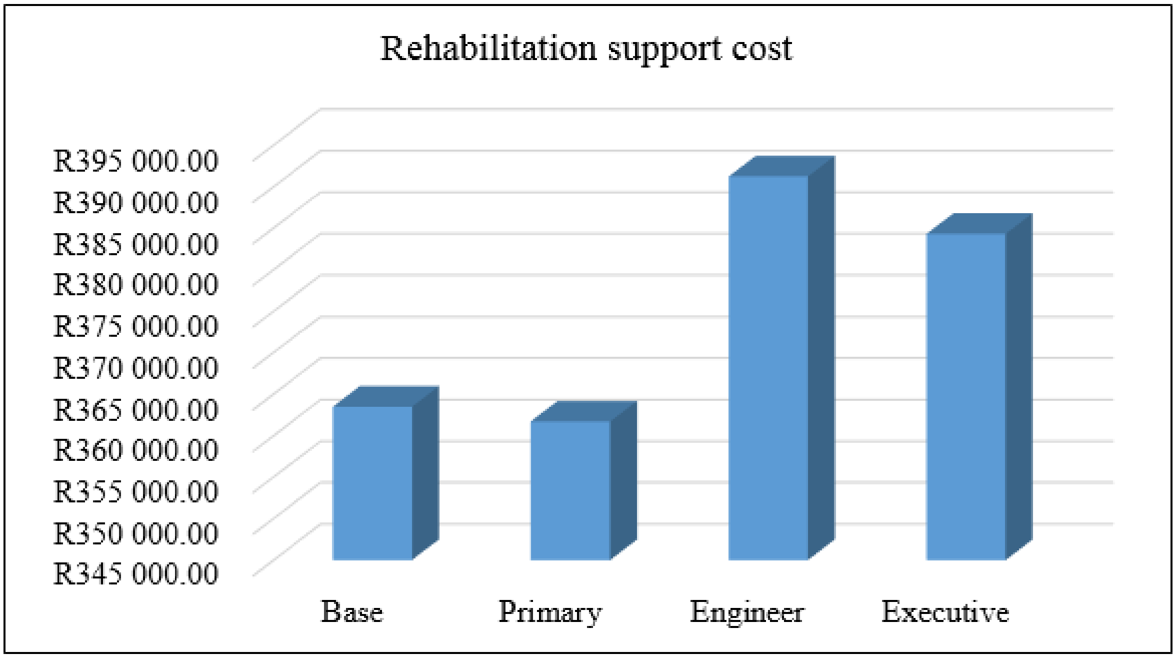


Figure 4-7: Comparison of results from the different spreadsheets against cost estimated with base calculations.

The difference in remedial support costs is due to the manner in which costs of support are estimated by each version of the model. The various versions of the model calculate the amount of grout for tendons from first principles, i.e. the difference between the volume of the drill hole and the volume of the tendon while the base calculations considers the actual number of grout bags used during the rehabilitation therefore accounting for spillage. That is the source of the R 1 780, 00 difference between the base calculation and the primary results as shown in Figure 4-8.

Both the executive and engineering spreadsheets assume that the roof and sidewalls of the tunnel where supported with the I-Beam system, unlike the base calculations and primary spreadsheet, which were customised for each wall of the tunnel. This resulted in a significant difference between the support costs estimated with the engineer, and the executive spreadsheet, and the base calculations. The source of difference between the engineer spreadsheet and the executive spreadsheet is the type of long anchors (i.e. the length of long anchors) and the cost of the long anchors. The support standards at both mines require 4.1 m long anchors while the ones recommended were 4.5 m long (Mine X, 2016c; 2016d; Mine Y, 2016a; 2016b).

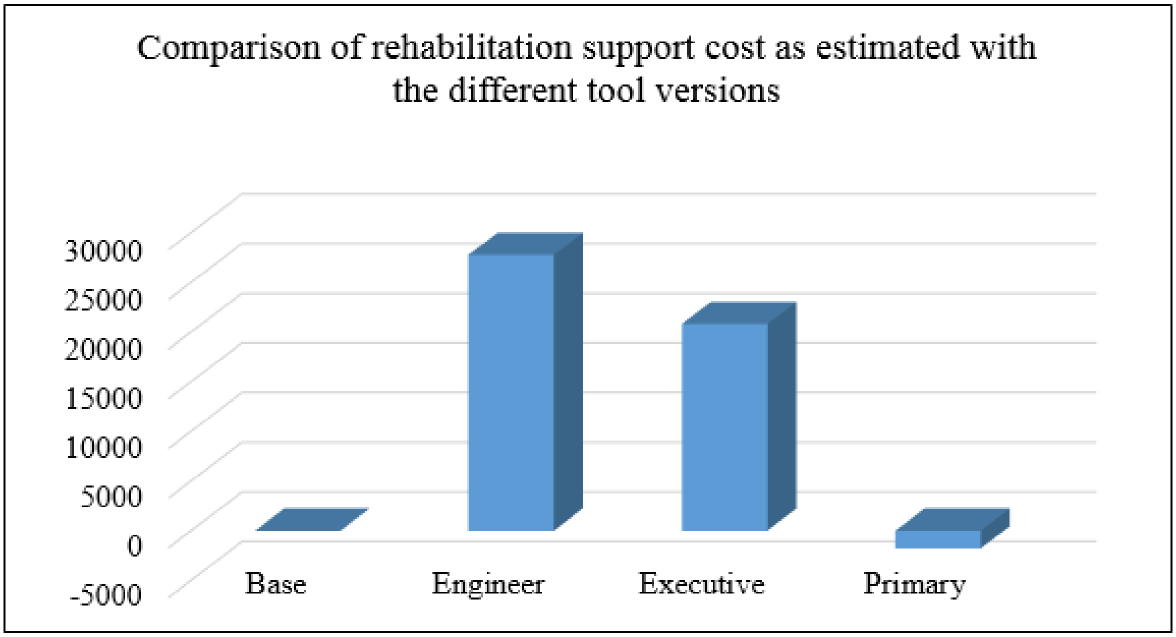


Figure 4-8: Variation in cost of rehabilitation support as calculated by each spreadsheet and by the base calculations.

In conclusion, the primary spreadsheet is the most accurate of the three spreadsheets. The costs estimated with this version were much closer to the costs calculated in the base calculations. This spreadsheet is easily adaptable to the specification of each case study. The executive spreadsheet gives reliable results when the support components are closer to the predefined support systems; this spreadsheet can be used by mine management. The engineer spreadsheet is more suitable where the support elements are installed to standard, where all walls of the tunnels are uniformly supported or where the engineer is evaluating costs of different support components that are installed to standard. The engineer spreadsheet is suitable for technical design by the mine’s rock engineering department using the mine’s predefined support standards.

4.2 Case Study 2: Rehabilitated Access

4.2.1 Background

This rehabilitation case study is from Mine Y. The rockburst damage is a slip type event associated with a 0.2 M_L seismic event that occurred in 2015. The rockburst damage occurred in a crosscut tunnel at a depth of 3.6 km. The tunnel was developed within quartzite rock. This crosscut is a flat development end intended for transportation of rock material between the working place and the shaft. The rockburst damage occurred in a weak zone in the vicinity of two faults and a seismically active dyke.

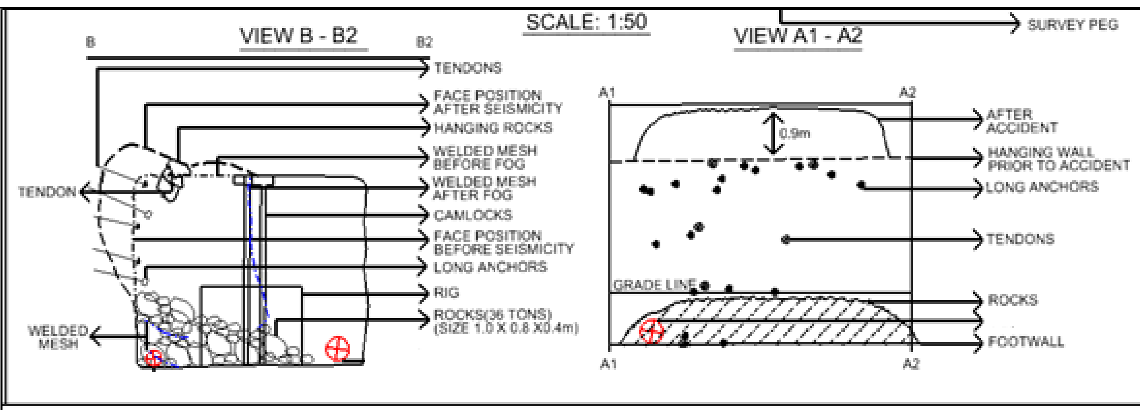
Table 4-3 summarises the rock engineering findings from the accident investigation. In this case study, there were five casualties. Two of which were dressing cases, a serious injury, a lost shift time injury and a fatality. The volume of rock dislodged was relatively small. This rockburst event resulted in a DMR Section 54 development ends full stoppage. The stoppage was lifted after nine weekdays (Nkuna, 2015; Mine Y, 2015).

Rigid support element were used to support this development end. The welded mesh and long anchors were found to not be up to standard. This may be due to lack of discipline during support installation or it may be that support standard has been updated since the support was installed in 2015. The delayed installation of a comprehensive support has significantly influenced the magnitude of the financial and personnel loss.

For remedial action, the development end was rehabilitated by cleaning the loose rock and installing the recommended support as soon as possible. It was assumed that the support was kept to standard at all times. As this is a development end, the damage or the Section 54 does not affect production directly, it might however delay the planned schedule, which is beyond the scope of this research. The development end was rehabilitated with yielding tendons, long anchors, weld mesh with lacing and shotcrete.

Table 4-3: Description of case study 2: Rehabilitation of damaged access (Mine Y, 2015)

Case study 2	
Description of accident	
Tunnel height : 3.7m	Tunnel width : 4.5m
Damage on hanging and sidewall Line metres : 5m Volume : 28.22 m^3 Area : 28.5 m^2	Number of Casualties Dressing case : 2 LTI : 1 SI : 1 Fatality : 1
Type of event : Slip failure (rockburst) Development end	Seismic event magnitude : 0.2
Geological features in the vicinity Within the Brazil Dyke; Two faults Quartzite host rock	
Name of support material	
2.1m 16mm Mphondo bolts @1m spacing 2.4m by 1.3m Welded mesh Binding spiral 3.6m Koepe rope @ 2m	
Support installation labour source Internal labour	



Rock engineering recommendations	
Course of action : Rehabilitate	
Line metres : 25 m Duration : 1 month	
Name of support material	
3.6m mechanical long anchors; Lacing; Weld mesh Durabar with a 350mm plate; Post Gunnite	
Support installation labour source Internal labour	

Figure 4-9 shows the damage experienced in the development end due to the rockburst. Failed rigid tendons and welded mesh are visible in the image. The locomotive used to transport waste rock is trapped near the development face.

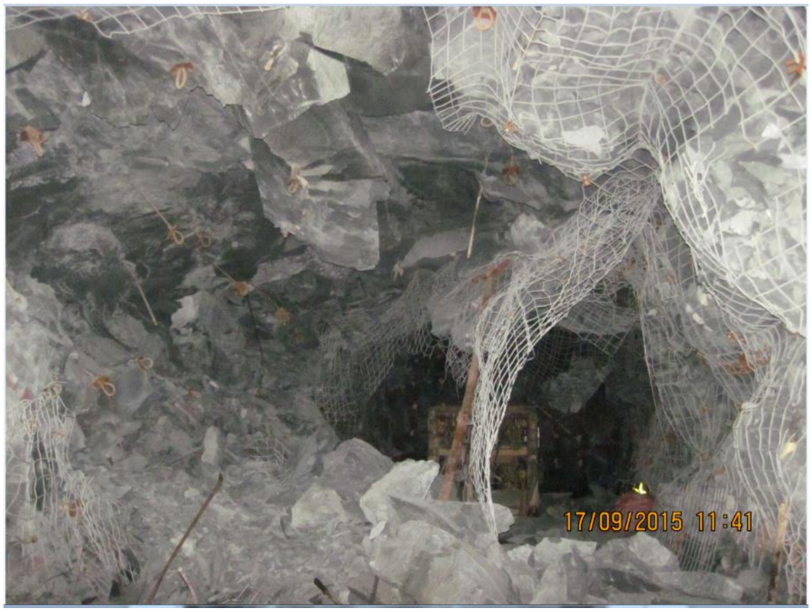


Figure 4-9: Rock mass ejected from the sidewall of the development end during the rockburst (Mine Y, 2015)

4.2.2 Case study results

In this section, the information from background and Table 4-3 was input into the various spreadsheets of the consequence-quantifying model. The executive, engineer and primary input interfaces of this case study can be viewed respectively in Table 8 3, Table 8 8 and Table 8 12 in the Appendix. The results are presented in this section and are later discussed and analysed in case study summary.

The consequences associated with this rockburst include personnel casualties, cost of rehabilitating the development end and remedial actions to rehabilitate the access tunnel. This development end had five casualties and a full development end Section 54 Stoppage. The stoppage may have resulted in levies, legal fees and penalties, which are not included in this study.

Executive spreadsheet results

This is a development end, therefore does not have direct impact on ore flow. Due to casualties, the mine lost R 1.9 million in medical and compensation costs to the affected parties. The damaged support cost R 21 700 and the rehabilitation support costs R 65 200. Presented in Figure 4-10 is the estimated financial loss, with details in Table 9-3 in the Appendix.

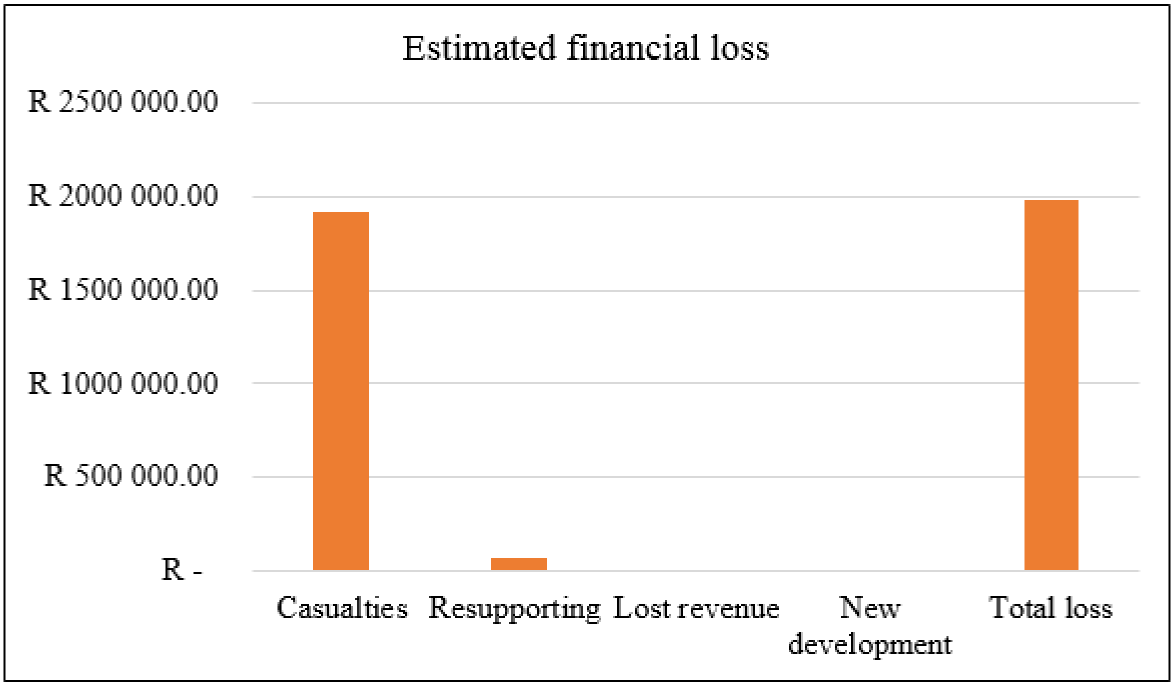


Figure 4-10: Summary of case study 2 using the executive spreadsheet

Engineer spreadsheet results

Figure 4-11 shows that the mine spent R 1.9 million in medical treatment and compensation to the affected personnel and/or their dependents. To rehabilitate the development end, the mine spent R 62 700. The mine experienced this rockburst loss due to late installation of comprehensive support.

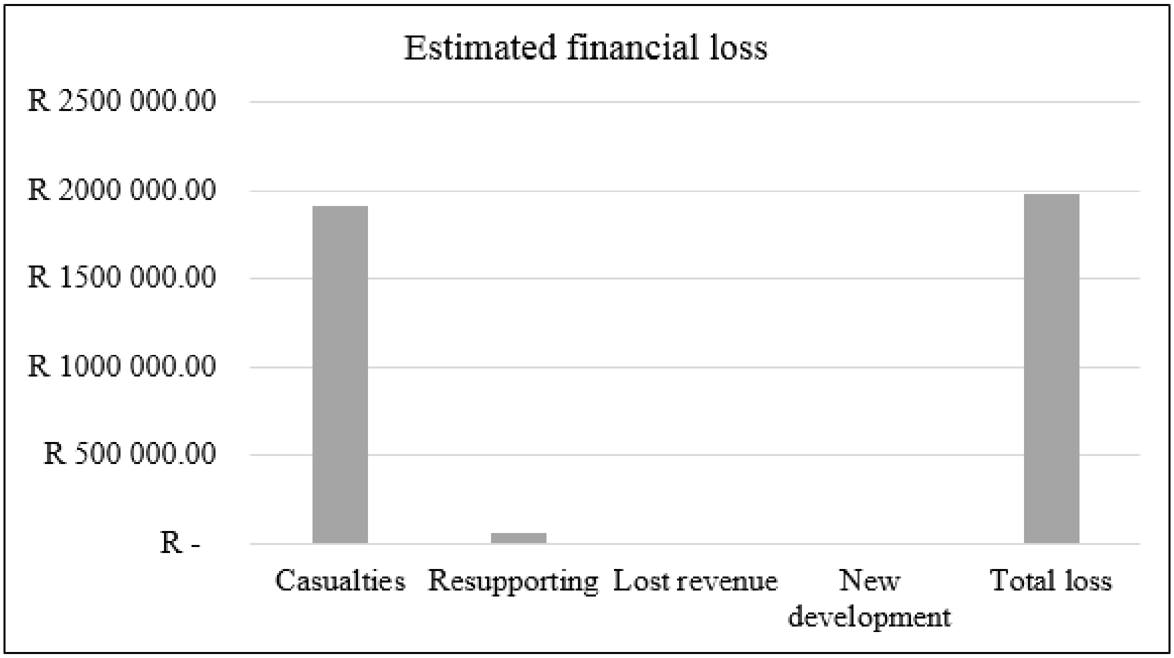


Figure 4-11: Summary of case study 2 using the engineer spreadsheet

Primary spreadsheet results

There was no revenue loss associated with this rockburst, as the development end was not yet connected to a production raise line. Due to casualties, the operation lost R 1.9 million in compensations. Rehabilitation support units cost R 64 400 as described in Table 4-3. A summary of the financial loss as calculated with the primary spreadsheet is presented in Figure 4-12 and a detailed cost estimate in Table 9-12 in the Appendix.

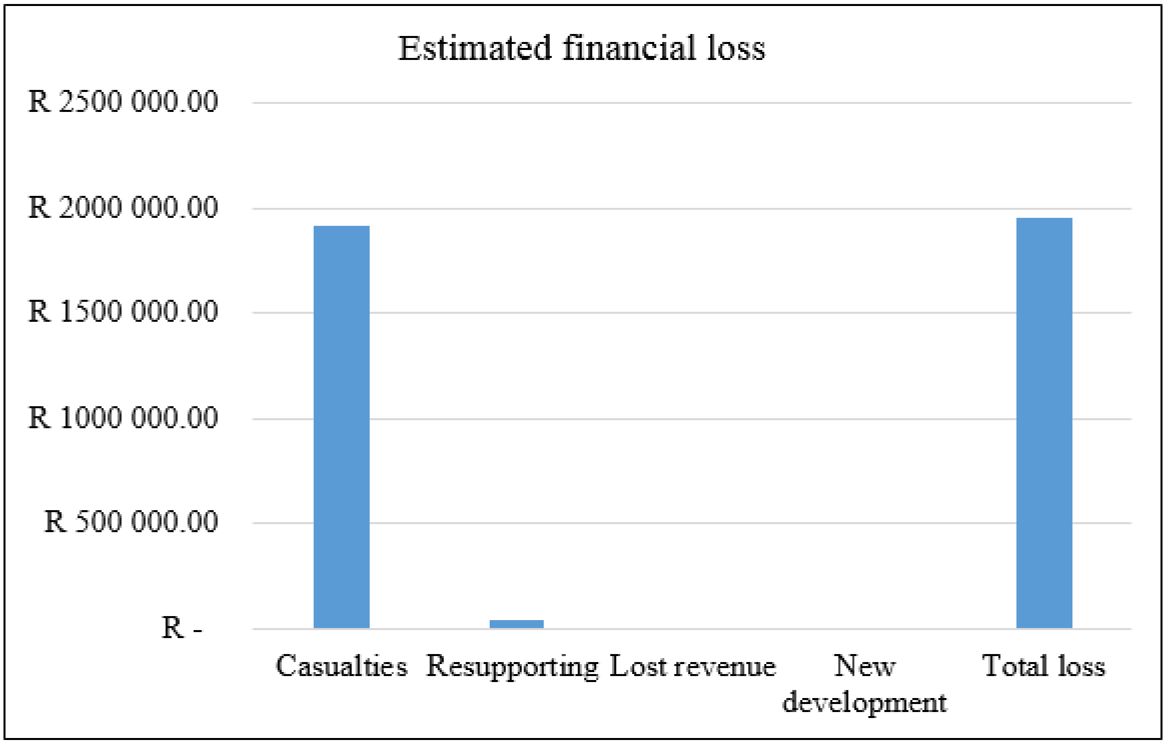


Figure 4-12: Summary of case study 2 using the primary spreadsheet

4.2.3 Value added by support systems

Figure 4-13 shows the cost of different energy absorbing support systems when compared to the financial loss. The difference between the two parameters is the possible financial value. In this case study, it is suggested that either of the two energy absorbing support systems defined in Chapter 2 could have been used.

The yielding support system would have cost the mine an estimated R 38 000 and could have preserved a value of R 1.96 million and prevented multiple casualties, while a yielding set support system would have cost R 105 000 over a span of 5 m and could have preserved a quantifiable value of R 1.86 million. Assuming that 4% of seismic events result in rockbursts in access tunnels and a consequence magnitude of R 1.96 million, this rockburst risk has a risk classification of 22 therefore should have been supported with yielding support as indicated in Figure 2-5.

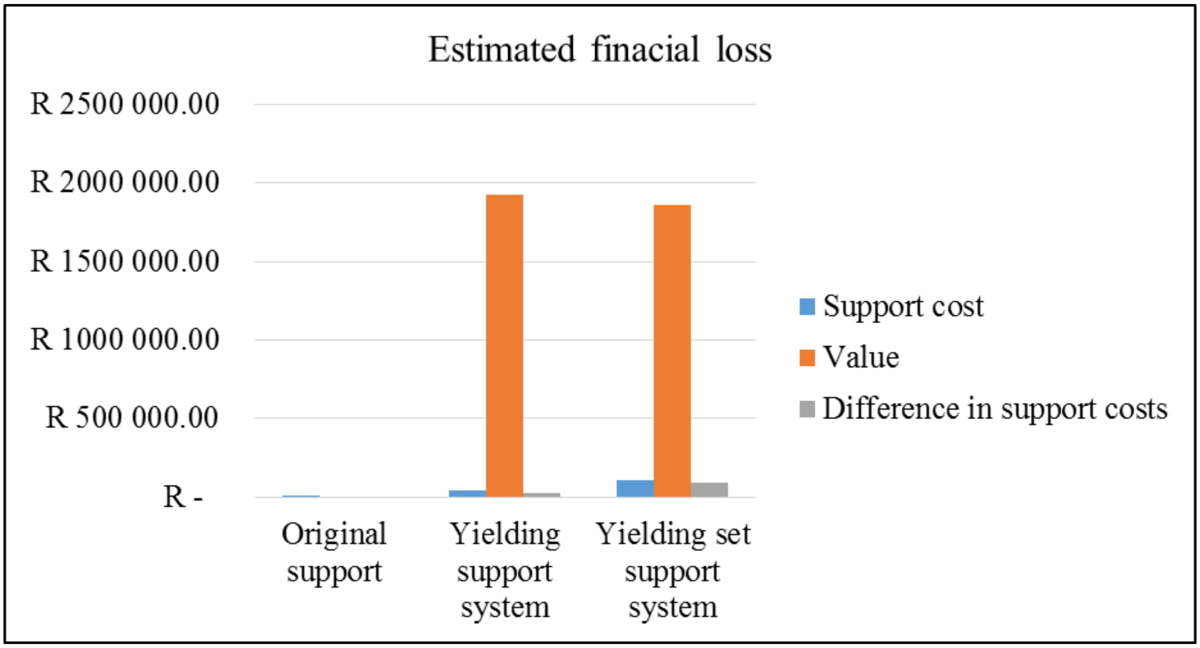


Figure 4-13: Average value added by support systems to case study 2

4.2.4 Case study summary

The volume of damage is relatively small and it could have been contained if an effective support system was in place. Similar support units were recommended before and after the damage of the tunnel, the difference is that rigid tendons were replaced with yielding tendons (Durabars). The support was not installed according to standard and it was lagging behind the recommended standard. This implies that the time it takes to install support plays a significant role in preserving integrity of tunnel and/or controlling rockburst. It is worth noting that installing the full support system as soon as possible and keeping support lags to standards could have contained this rockburst event.

Support costs are the source of difference in estimated financial loss with each spreadsheet. The remedial support costs estimated with the primary spreadsheet are the lowest and the executive spreadsheet calculated the highest costs.

4.3 Case Study 3: New Access Case Study

4.3.1 Background

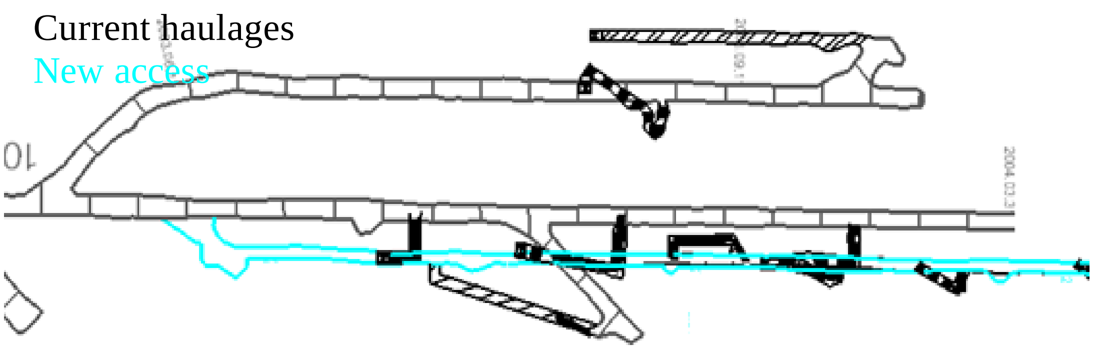
This case study is a slip rockburst event associated with a 2.8 M_L seismic event that occurred in 2009. The damage occurred at 3.2 km below mean sea level in a crosscut tunnel excavated within quartzite rocks. The damage happened in the west side of the mine, known as the “west mine”. Seismic events dominate the west mine due to the high prevalence of geological structures when compared to the east mine. This tunnel was developed through Jean’s Dyke, the Sunday Dyke and the Open Dyke; all of these dykes are known to be seismically active. The rockburst resulted when a slip occurred along the Open Dyke resulting in closure of the tunnel. The relevant information is summarised in Table 4-4, a summary of rock engineering findings and recommendation made after the investigation of this rockburst event.

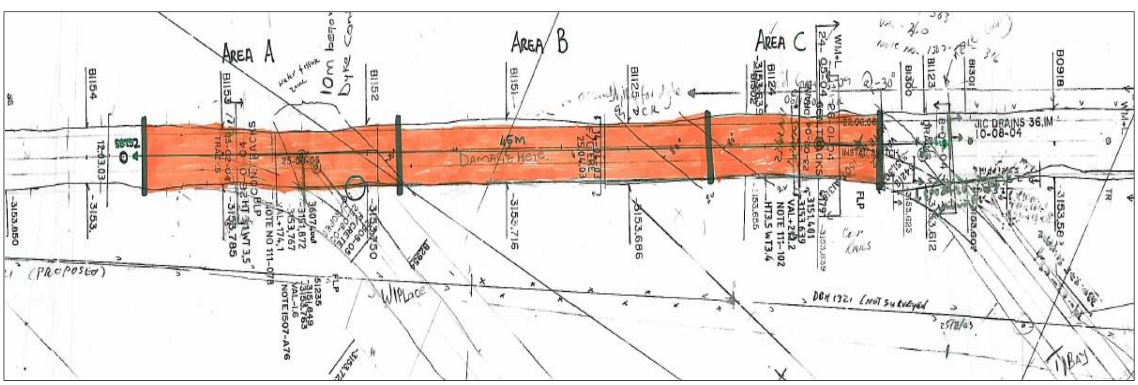
Splitsets (rigid tendons) and shotcrete were used to support the area where damage occurred. This is not up to the standard defined in Figure 3-5 and the special recommendations made for dykes (Mine X, 2009).

For remedial action, a new crosscut tunnel was developed in order to access the producing raise line. For this research, it was assumed that the recommended remedial support was installed according to standard and as recommended in Table 4-4 during the development of the new access tunnel. It was additionally assumed that the reef could not be accessed and mined, therefore the crews lost three weeks of production while a new working place was established. Each crew was allocated a 110 t of ore target per week. From previous experience, it takes an average of three weeks to move and establish a new working place (R Mulaudzi 2016, pers.comm. 29 November). This is the time of production lost and will affect the revenue of the mine.

Table 4-4: Description of case study 3: Developing a new access (Mine X, 2009)

Case study 3	
Description of accident	
Tunnel height: 3.7 m	Tunnel width: 3.7 m
Damage: Both sidewalls Line metres : 41 m Volume : 31 m^3 Area : 50 m^2	Number of Casualties LTI : 0 SI : 0 Fatality : 0
Type of event : Slip failure (rockburst)	Seismic event magnitude : 2.8 ML
Geological features in the vicinity : Open Dyke	
Name of support material	
Tendons 2.1 m splitset ; Gunnite (shotcrete)	





Rock engineering recommendations	
Course of action : Develop new access	
Line metres : 315 m Duration : 14 months	
Name of support material	
Durabars at 2m diamond pattern 10m either side of dyke Ripple bars elsewhere; Mesh and lacing ; 3.6m Koepe rope (LA)	

4.3.2 Case study results

The following results were obtained when the information in Table 4-4 was input into the executive spreadsheet of the model as shown in Table 9-4, the engineer spreadsheet in Table 9-9 and Table 9-13, the primary spreadsheet. The data in Table 4-4 was input into the model as described in Chapter 3. The results are discussed in this section.

Executive spreadsheet results

A 315 m new access was developed in order to replace the blocked tunnel and to access the reef. The damaged support units cost R 139 500 and the rehabilitation support units cost R 1.30 million. The results are shown in Figure 4-14, with details in the Appendix in Table 9-4. The total loss incurred because of this rockburst amounts to R 7.07 million.

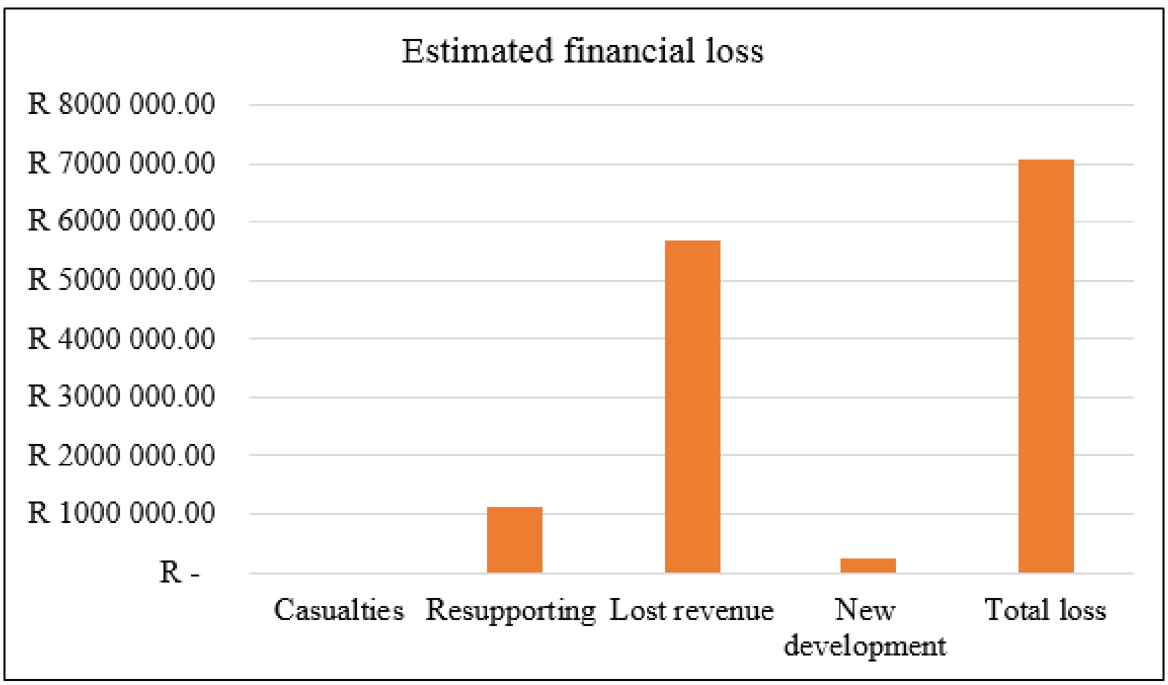


Figure 4-14: Summary of case study 3 using the executive spreadsheet

Engineer's spreadsheet results

A new 315 m access was developed in order to provide access to the reef. The damaged support units cost R 93 200 and the rehabilitation support cost R 665 300. A 21-member crew developed this new access over a period of 14 months. During the moving out and establishing a new working place process, the crews lost three weeks of production amounting to R 5 692 500, 00 in revenue. A summary of cost is presented in Figure 4-15, with details in Table 9-9 of the Appendix.

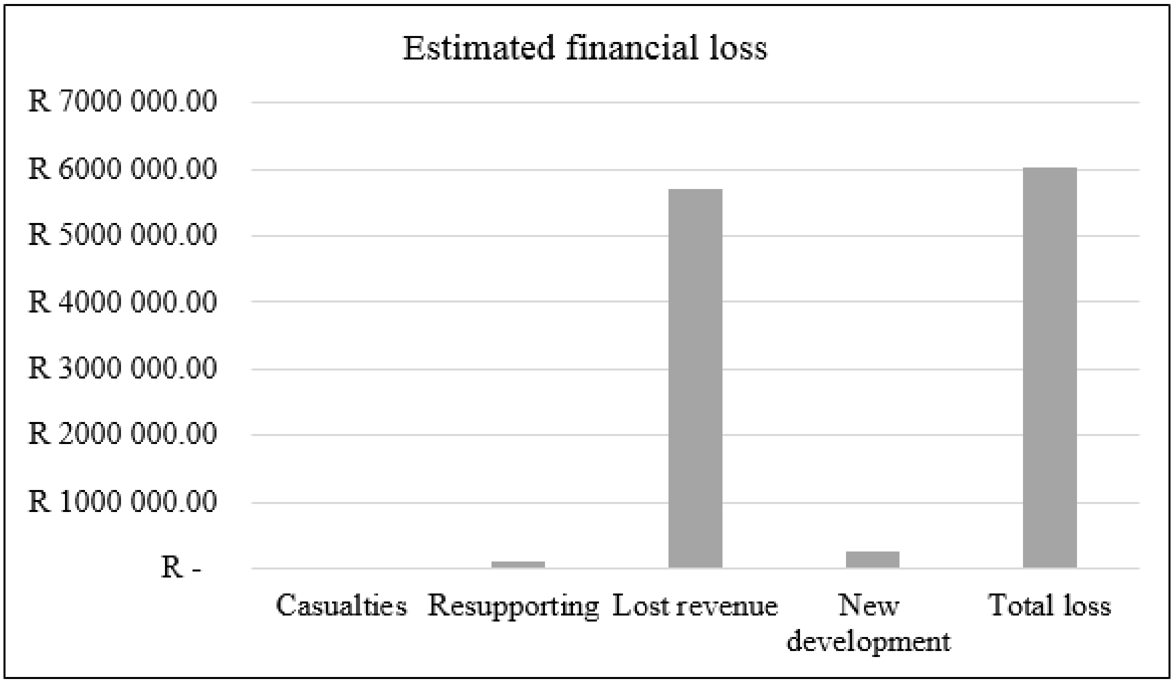


Figure 4-15: Summary of case study 3 using the engineer spreadsheet

Primary spreadsheet results

In this version the rehabilitation support costs R 652 400. The blocked tunnel resulted in R 5.69 million revenue loss over the three weeks when the crews were unable to produce ore. The financial losses are presented in Figure 4-16 and in Table 9-13 in the Appendix.

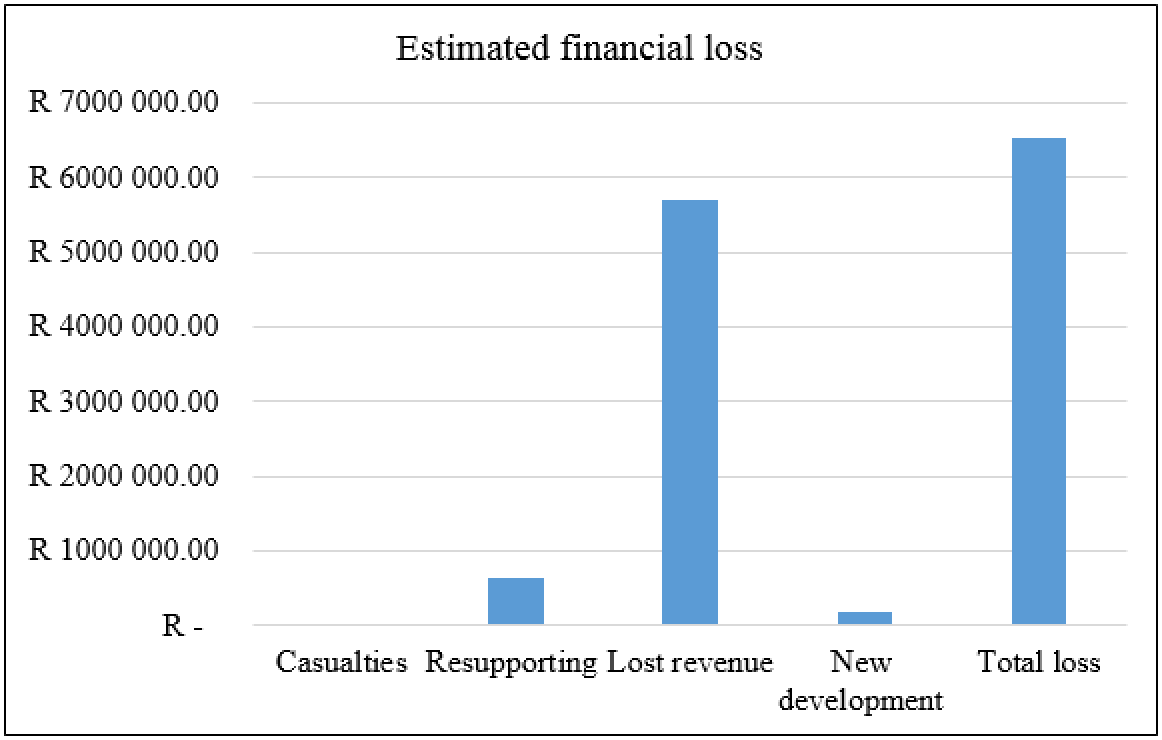


Figure 4-16: Summary of case study 3 using the primary spreadsheet

4.3.3 Value added by support systems

Figure 4-17 which depicts cost of energy absorbing support systems when compared to the financial loss incurred during the rockburst event, in order to determine the financial value of the energy absorbing support system. It is suggested that either of the energy absorbing support systems defined in Chapter 2 could have been used to support the tunnel during the development of the tunnel. The suggestion is based on the geology through which the crosscut was developed. It was developed through three consecutive seismically active dykes.

At an average total financial loss of R 7 million, this consequence is considered a high impact and a 4% probability of a rockburst in a tunnel as indicated in Table 3-1, this rockburst has a risk classification of 22, the tunnel should have been supported with yielding support. The difference between the suggested yielding set support system and the cost of damaged support were calculated with the executive, engineer and primary spreadsheets. The results are R 728 400, R 782 300 and R 766 000 respectively and thus at an average additional cost of R 0.76 million and an estimated average value of R 5.80 million as shown in Figure 4-17 could have been realised with a yielding set support system. If a yielding support systems was used, it would have cost the mine R 0.38 million and could have created a value of R 6.33 million.

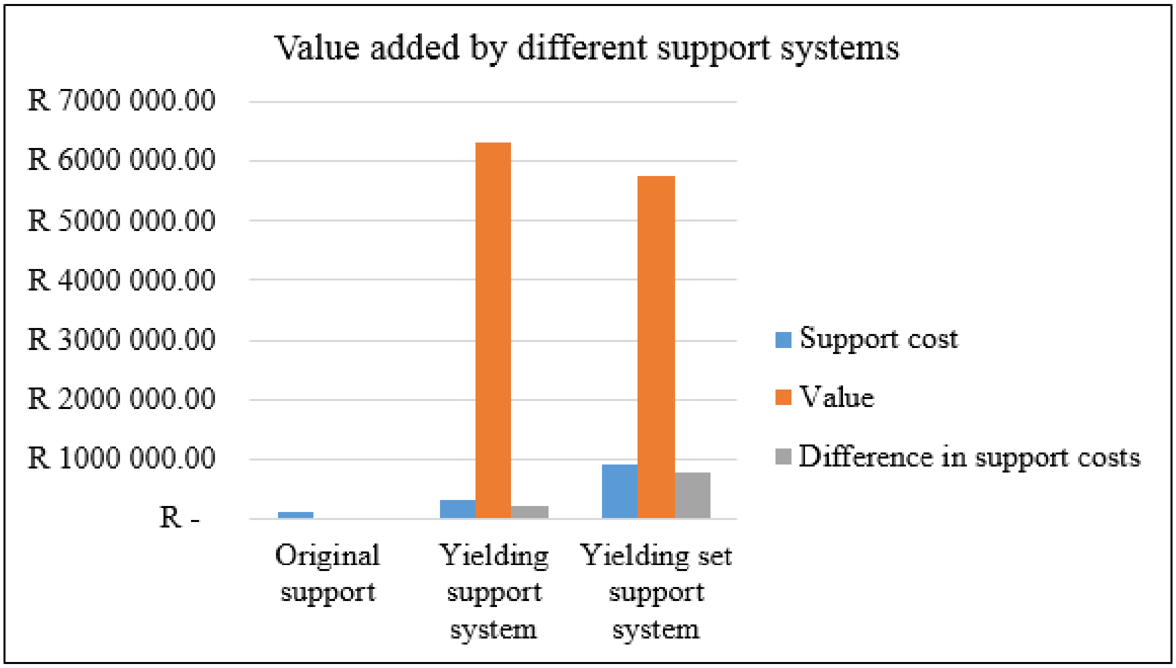


Figure 4-17: Average value added by support systems to case study 3

4.3.4 Case study summary

Minimal rigid support was installed in a crosscut developed through dykes. The splitset and shotcrete support was not adequate support for this tunnel. A support system suitable for dynamic loading conditions may have been able to contain this rockburst. Interrupted ore flow resulted in the highest financial loss. Figure 4-14, Figure 4-15 and Figure 4-16 show a pattern among the results of this case study; for the remedial support costs, the executive spreadsheet depicts the highest costs and the primary spreadsheet has the lowest costs estimates. The difference between the two extremes is R 477 500. This is attributed to the 50 mm layer of shotcrete described in the rigid support system of the executive spreadsheet while the other two spreadsheets do not have a layer of shotcrete. This is a standard feature of the executive spreadsheet and thus overestimates the support costs in this case because the support components recommended to support the new tunnel deviates significantly from predefined support systems.

The geology through which this tunnel was developed could have been considered to be high risk. This means that the excavation required possibly a conservative support system like a yielding support or yielding set support.

4.4 Case Study 4: Abandoned Access

4.4.1 Background

The case study is a slip rockburst event associated with a 2.1 M_L seismic event that occurred in 2013. The damage occurred in a tunnel at a depth of 3.6 km excavated within lava rock mass. The damage happened in the east side of the mine, known as the "east mine". The east mine is less seismically active when compared to the west mine (Mine X, 2016d). The rockburst resulted when a slip occurred along the seismically active PE Dyke resulting in closure of the travelling way at the reef intersection and gaping of two joint sets along the traveling way (Mine X, 2013). All these information is summarised in Table 4-5.

Rigid support was used to support this access tunnel. A few split sets and wooden I-Beam sets were used to support the travelling way. The rock engineering report states that this support was not up to the recommended standard as the recommended yielding tendons and mesh with lacing were missing (Mine X, 2013). Only eight split sets were used along the visible length of the travelling way (Mine X, 2013). The travelling way is 2.8 m wide instead of the 1.8 m recommended width (Mine X, 2013).

After the assessment, it was concluded that the travelling way was to be abandoned and barricaded off. For movement of material to the panel, a mono winch rope was to be extended from the level above (Mine X, 2013). During the setting up of new material route, it is assumed that three crews lost a week's worth of production. A crew has a weekly target of 110 t at an average grade on 10 g/t.

Table 4-5: Description of case study 4: Abandoned access (Mine X, 2013)

Case study 4	
Description of accident	
Tunnel height : 2 m	Tunnel width : 2.8 m
Damage Hangingwall Line metres : 8 m	Number of Casualties LTI : 0 SI : 0 Fatality : 0
Type of event : Slip	Seismic event magnitude : 2.1 M_L seismic event
Geological features in the vicinity Two joint sets PE Dyke	
Name of support material	
1.5 m x 1.1 m timber composite packs 3 m apart Stromaster elongate support units and laggings (“timber sets”) Split sets total of 8 through the entire length	
Rock engineering recommendations	
Course of action : Abandon and use alternative material transport route	

Figure 4-18 shows the blocked holing of the monowinch travelling way, with riggings and ropes trapped by broken rock mass.

Figure 4-18: Blocked monowinch travelling way (Mine X, 2013)

4.4.2 Case study results

The following results were obtained when the information in Table 4-5 was loaded into the executive spreadsheet of the model in Table 9-5, the engineer spreadsheet in Table 9-10 and primary spreadsheet in Table 9-14. The results are discussed in the section that follows.

The travelling way was abandoned after the rockburst damage because it was decided that travelling was at the end of its useful life and it would be less costly to extend a monowinch rope from a different level. This blocked travelling way was barricaded and abandoned, and different access was used to transport material to the stope. Figure 4-19 below and Table 9-5 in the Appendix present the financial loss associated with this rockburst. There are negligible remedial costs associated with this incident as there is only revenue loss to be considered.

Executive spreadsheet results

The damaged support units cost an estimated R 44 100. Lost revenue of R 1.9 million was experienced when the monowinch was being extended. The financial loss is shown in Figure 4-19.

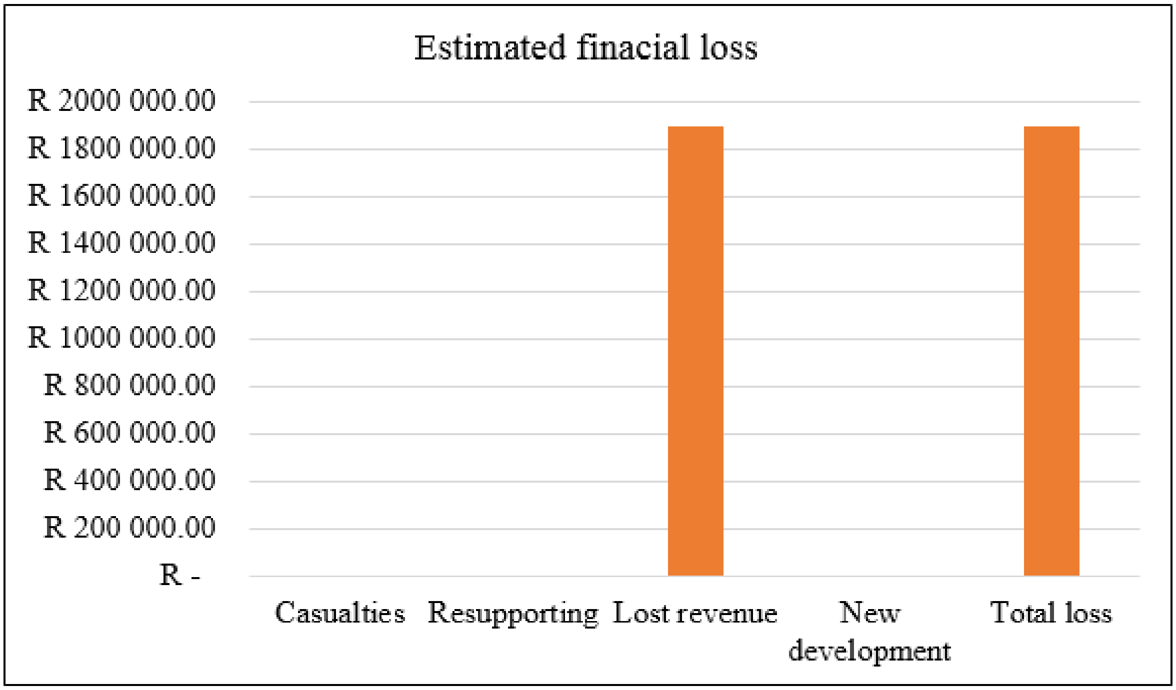


Figure 4-19: Summary of case study 4 using the executive spreadsheet

Engineer spreadsheet results

The mine lost a revenue of R 1 897 500 during the one week which the monowinch was being extended to reach the affected panels. The financial loss is presented in Figure 4-20.

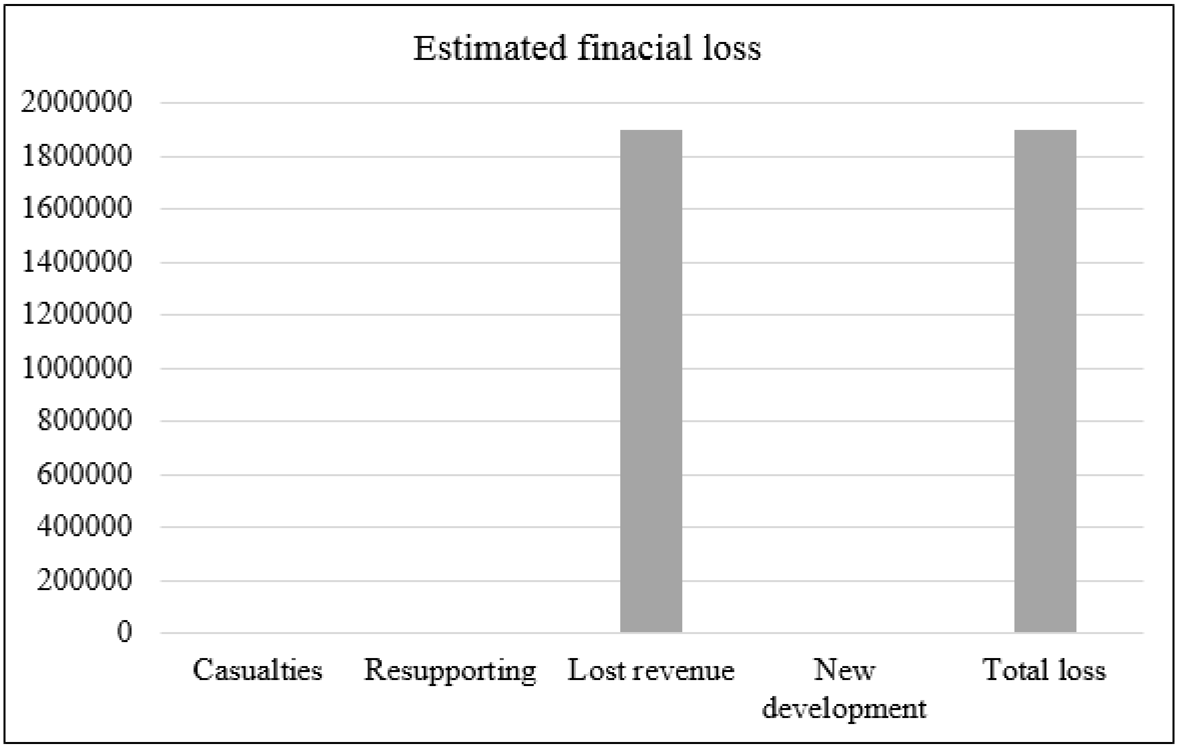


Figure 4-20: Summary of case study 4 using the engineer spreadsheet

Primary spreadsheet results

Financial losses associated with this rockburst are presented in Figure 4-21 and Table 9-14 in the Appendix. The figures show a lost revenue of R 1 897 500 during the one week of extending the monowinch to reach the affected panels.

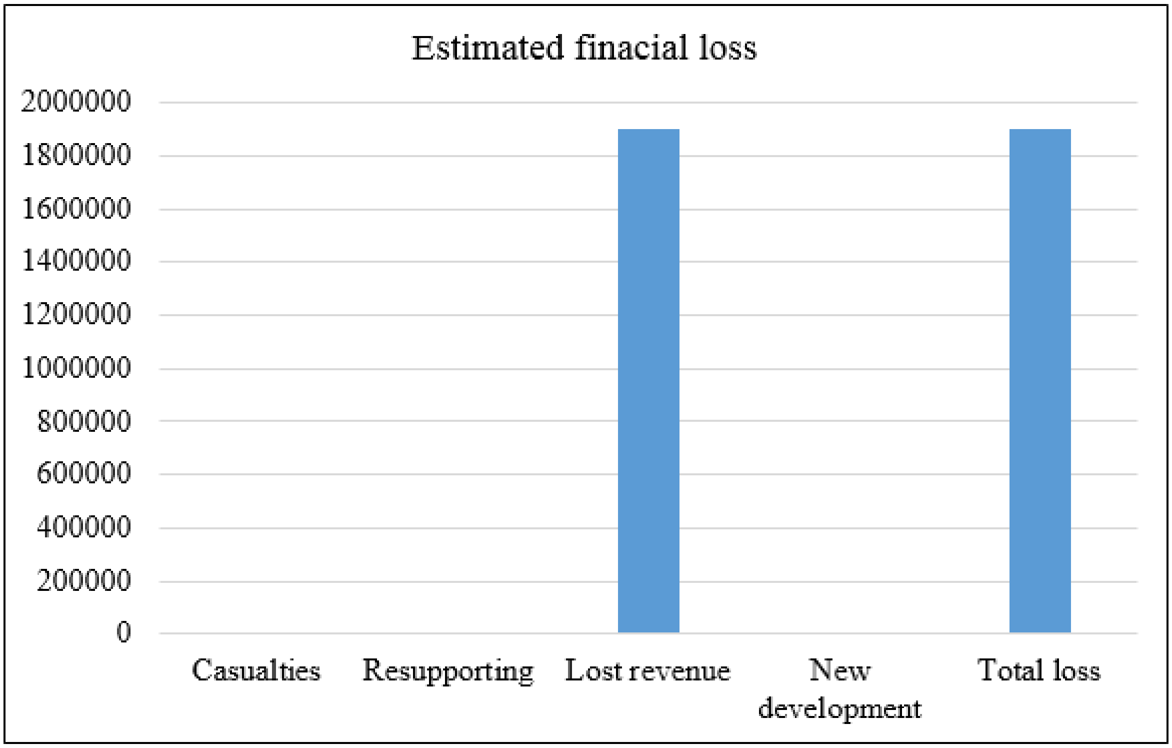


Figure 4-21: Summary of case study 3 using the primary spreadsheet

4.4.3 Value added by support systems

In this section, the financial value that could have been added by yielding support system is evaluated against the financial loss incurred due to the rockburst. The average financial value is summarised in Figure 4-22. In this case study, it is suggested that the yielding support system that should have been used during development as it was recommended, this is based on the risk classification of the rockburst. It is assumed that the access wouldn’t have failed if yielding support system was installed.

The difference between the suggested yielding support system and the cost of damaged support as calculated with all spreadsheets giving a difference of R 17 300, and a possible estimated average value of up to R 1 940 300. Assuming the yielding set support system did not fail, the operation could have saved an average of R 1.94 million in value. Since this access was abandoned after rockburst, it is possible to consider that the travelling has outlived its useful life and the value of the initial investment into this travelling way has been fully realised. However, this may not be entirely true as material transportation line had to be extended from the top level to the panels which were previously serviced by this monowinch travelling way.

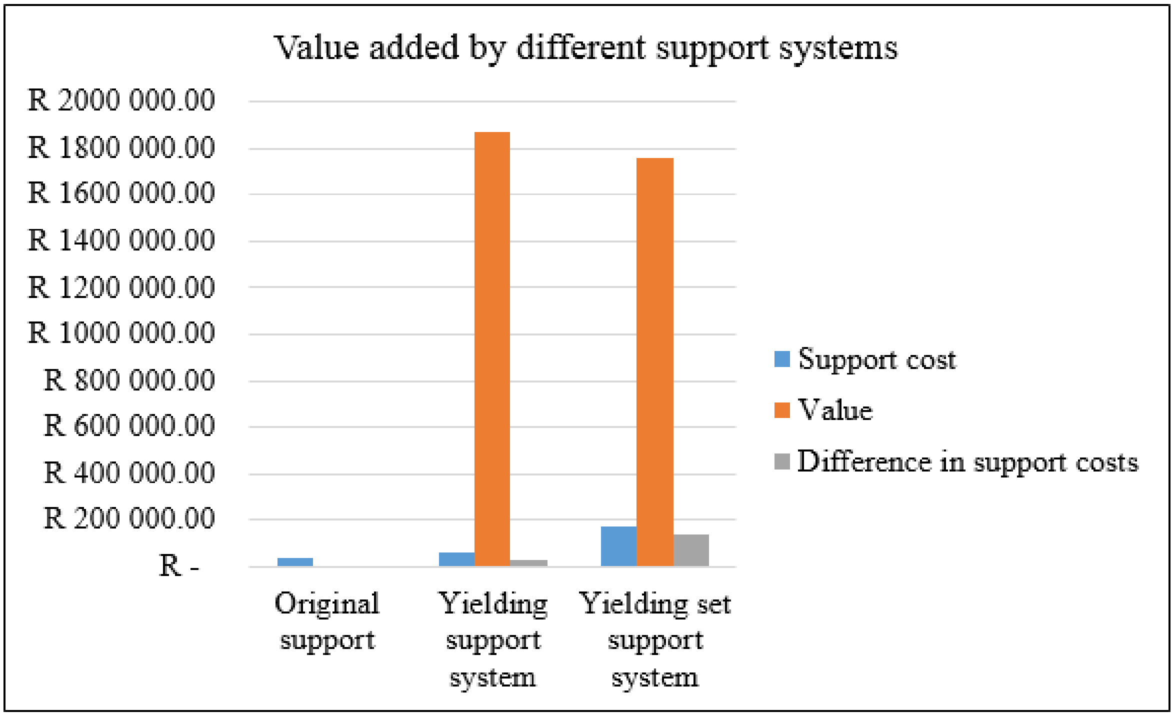


Figure 4-22: Average value added by support systems to case study 4

4.4.4 Case study summary

The travelling way was poorly supported; a splitset per row over a length of eight metres in a 2.8 m wide tunnel is insufficient and not up to the mine support standard. The travelling way width of 2.8 m was a metre wider than the recommended width (Mine X, 2013). The “timber sets” were not to mine standard either, and lacked void fill material. The now blocked travelling way had minimal financial implications. Abandoning this monowinch travelling way implies that in was unnecessary to open it again as a more economical alternative was available.

The estimated support costs vary. The executive spreadsheet produced the highest estimated support costs and the primary spreadsheet estimated the lowest support costs. The difference in support costs between the executive the primary spreadsheets is R 10 000. Results from the engineer's spreadsheet are R 800 higher than that of the primary spreadsheet. The executive model assumes that the rigid support was installed to standard therefore it over estimates the costs. The primary spreadsheet used the information as defined in the background as is. As such, it can be concluded that the primary model produces the closest estimate to the actual costs.

4.5 Summary

In this chapter, the different spreadsheets of the consequence-quantifying model were used to analyse, in detail, four case studies. The first case study is a benchmark to help evaluate the accuracy of the different spreadsheets. The benchmark case study indicates that the primary spreadsheet is the most accurate of the three as it is adaptable to different scenarios. The executive spreadsheet gives the highest estimates but will yield accurate results if the support components being evaluated are comparable to any of the predefined support systems.

The second case study shows the impact of installing support to standard as timely as possible. The case study shows that the rockburst could have been contained if appropriate support was installed timely.

The third case study shows the greatest loss of all the case studies. The tunnel was developed through three dykes, with a history of seismicity, however it was support with rigid tendons and shotcrete. The tunnel required a conservative and comprehensive support system such as the yielding set or the yielding support system.

Case Study 4 shows a scenario where a tunnel may have reached the end of its useful life. The access tunnel was abandoned after it experienced a rockburst, this was likely because a cost-effective alternative was available.

All the case studies had a risk classification of 22 because there was a probability of rockburst in tunnels of 4% and all had financial losses over R 1 million, thus they should have been supported with energy absorbing support system.

5 CHAPTER 5: ANALYSIS OF CASE STUDIES

This chapter seeks to understand the functionality and accuracy of the three versions of the consequence-quantifying tool and their limitations. This is achieved by analysing the results of the cases studies against the objective of the research.

The results obtained from the four case studies are analysed in this chapter. In case studies 1, 3 and 4, the biggest source of financial loss is lost revenue while in Case study 2 personnel casualties contributed significantly to the total estimated financial loss. After the rockburst damage, some of the access tunnels were reopened and re-supported. The graph in Figure 5-1 that the cost of remedial support was always higher than the cost of the damaged support units in case studies 1, 2 and 3.

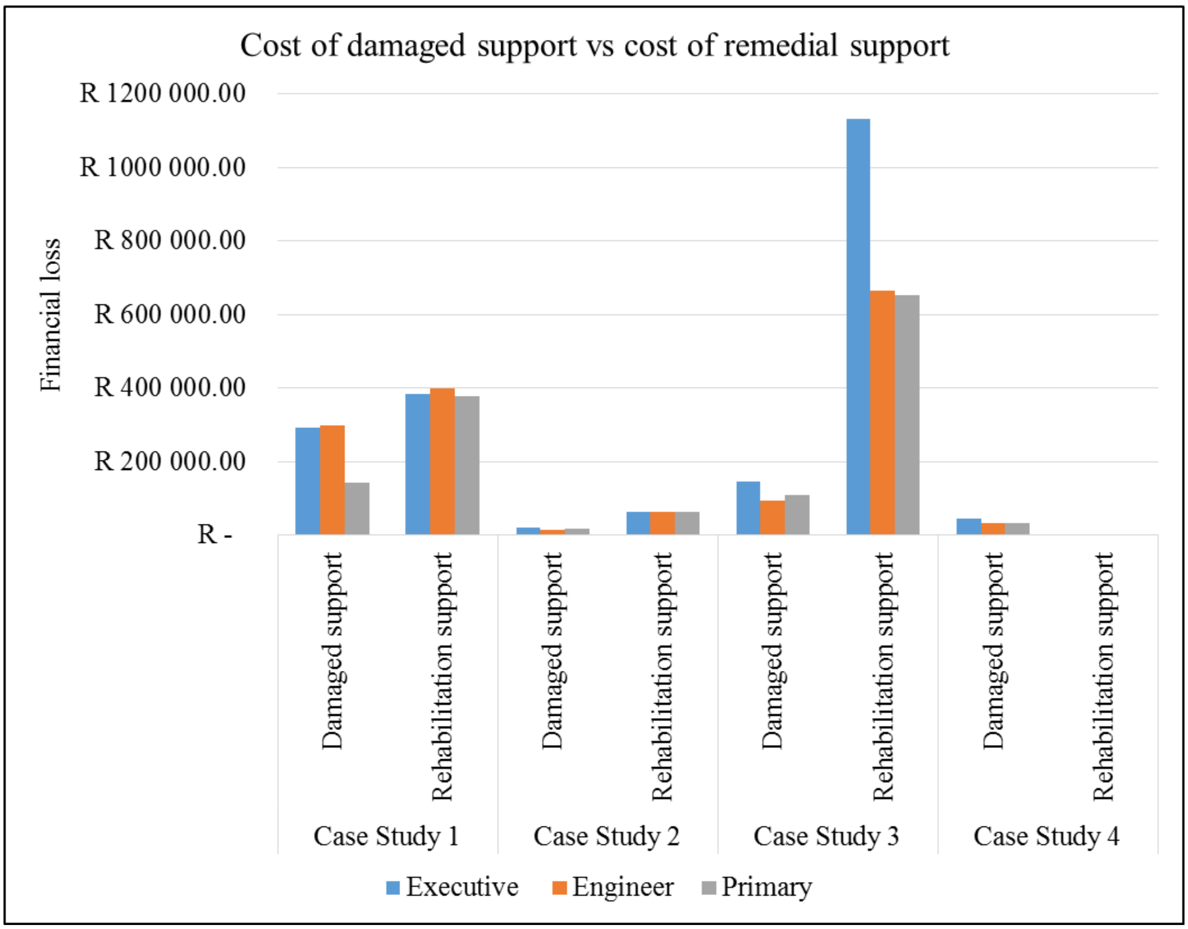


Figure 5-1: Distribution of original and remedial support costs of the case studies

In Figure 5-2, the primary spreadsheet estimated the lowest support cost of all spreadsheet in all case studies except for Case Study 3, where the engineer spreadsheet resulted in the lowest support cost estimates. The executive spreadsheet resulted in the highest cost estimates throughout all the case studies, except for Case Study 1 where the engineer spreadsheet had the highest cost estimates.

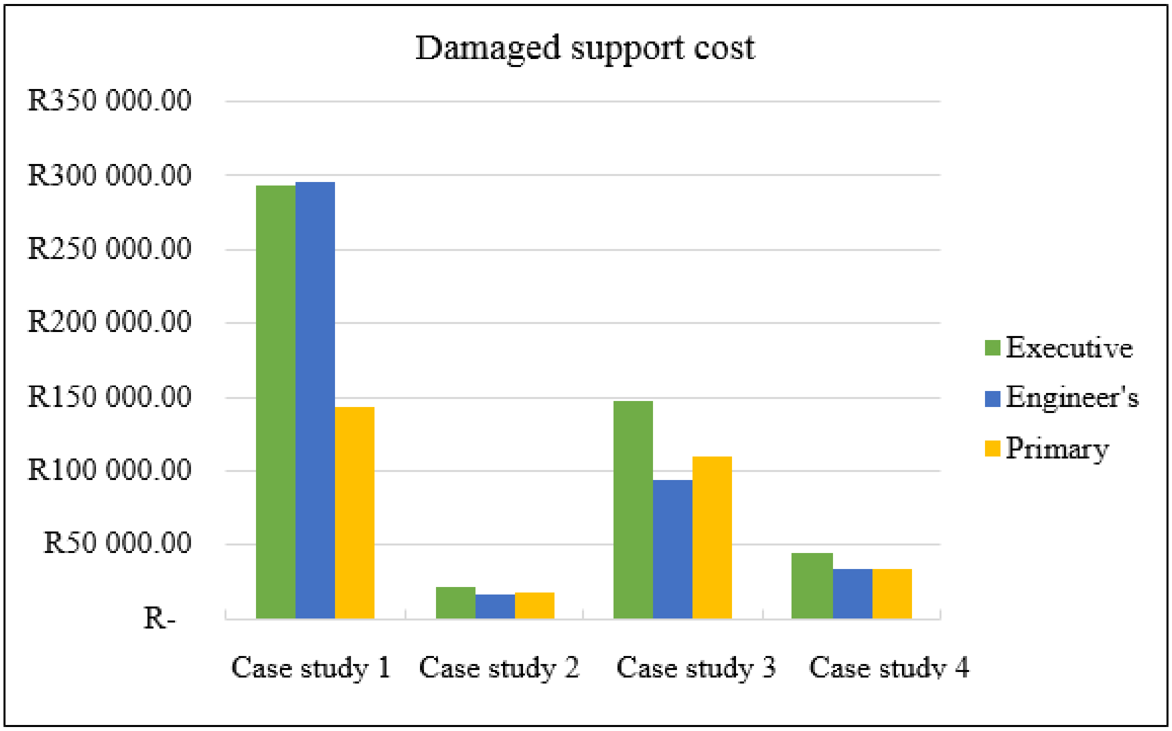


Figure 5-2: Cost of damaged support units

Figure 5-3 shows rehabilitation support costs of all case studies. The different spreadsheets estimated similar results for all case studies, except for case study 3, where the executive spreadsheet was an outlier with estimated support costs above a million Rands. This is because the predefined rigid support system has a standard 50 mm layer of shotcrete, while the recommended support for this case study does not include shotcrete.

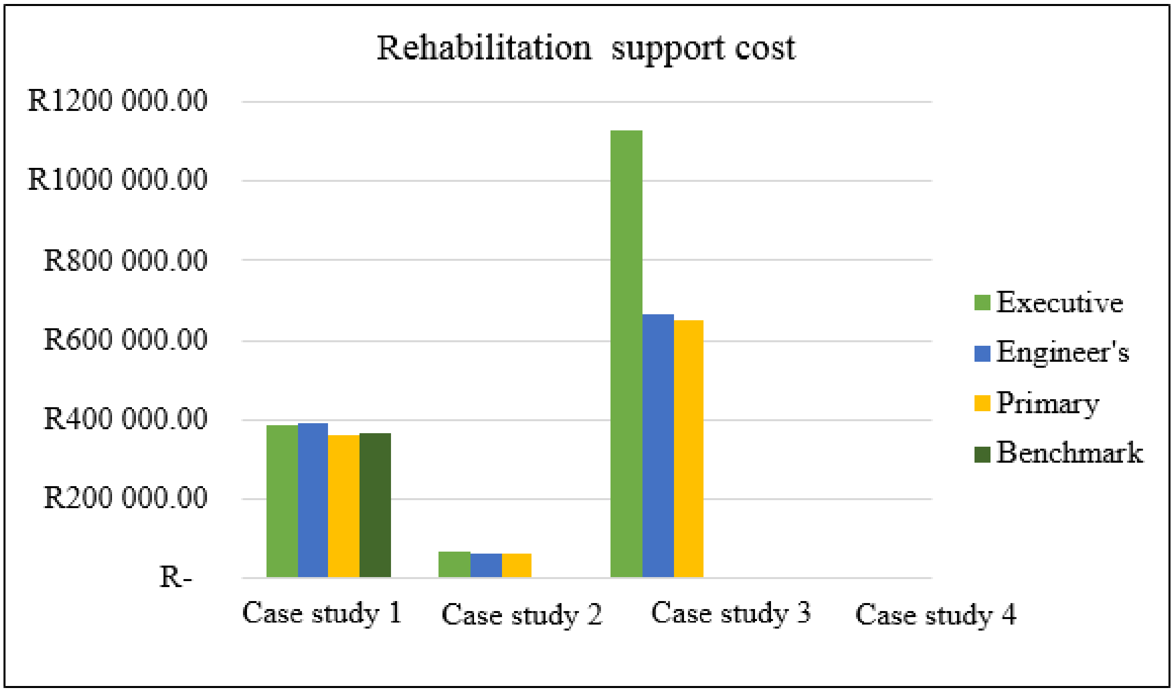


Figure 5-3: Cost of rehabilitation support units

Figure 5-2 and Figure 5-3 compares cost of support units from different spreadsheets for all the case studies. Executive spreadsheet's results in Case Study 3 can be regarded as outlier as it can be seen that the spreadsheets produce consistent results.

Figure 5-4 shows the estimated rehabilitation support costs for the case study 1 derived from the model spreadsheets compared to the benchmark (i.e. case study 1) support costs estimated at the operation. The primary spreadsheet gave results closest to those of the benchmark case. This spreadsheet is easily adaptable to the conditions as described on the base case background. The engineer's model estimated the highest costs. In the base calculation, only the sidewalls were rehabilitated while the engineer's and executive spreadsheets of the model does not consider this. The model assumes that both sidewalls and roof were rehabilitated.

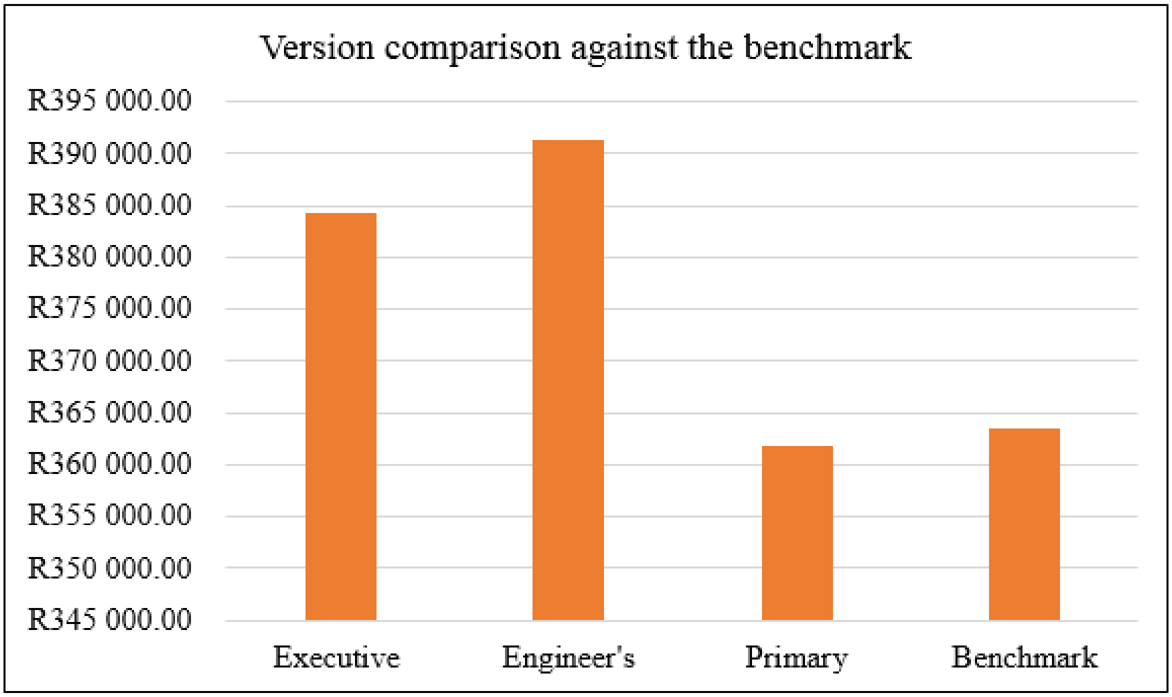


Figure 5-4: Rehabilitation support cost from Case Study 1

In all the case studies except Case Study 4, the remedial support costs were higher than the cost of the damaged support. The increase in costs is due to the additional linear metres that had to be rehabilitated, the duration of rehabilitation and the new support components or support system that had to be installed. In all the case studies, the financial loss due to the rockburst is significantly higher than the cost of energy absorbing support systems as shown in Figure 5-5. Case Study 4 did not have any significant remedial costs as the access was abandoned after the rockburst event.

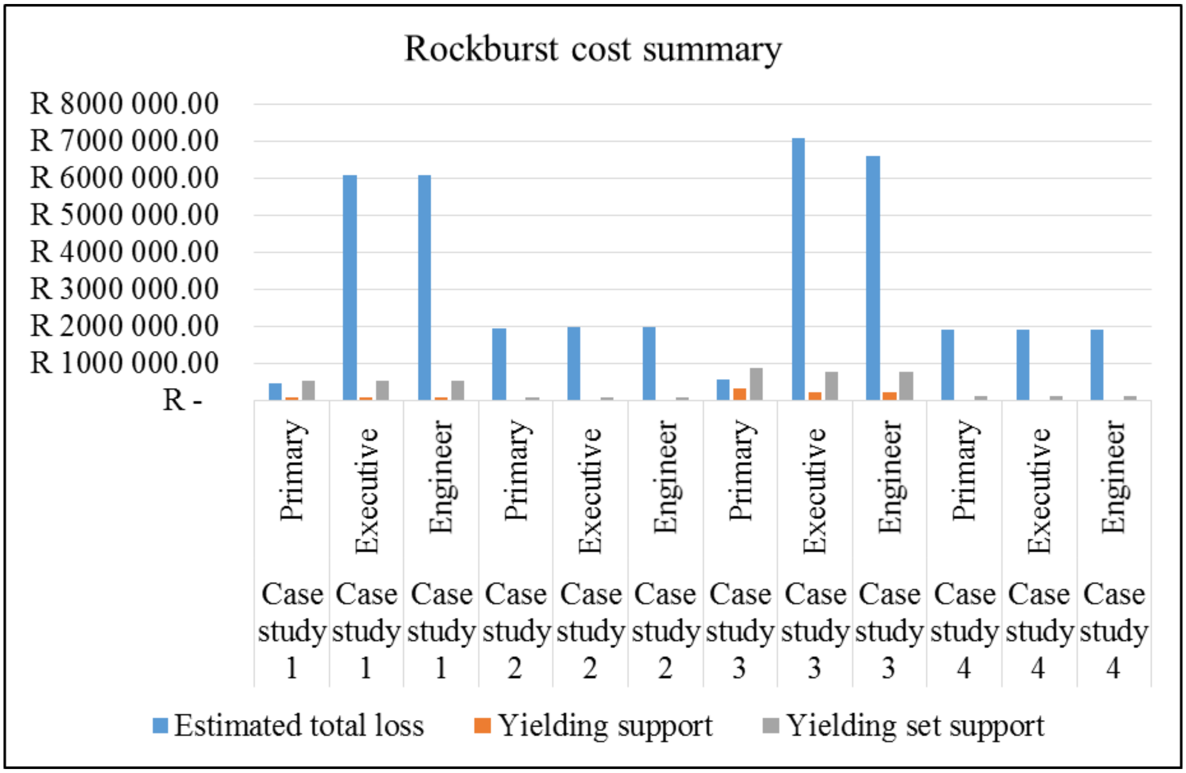


Figure 5-5: Cost summary of the case studies

In a given case study, personnel casualties and revenue losses remain relatively constant throughout all the different spreadsheets of the consequence-quantifying model. Variation appear when estimating the cost of support. The three main sources of variation in support costs are the difference between recommended support components and the predefined support systems. The recommended support components that do not match the components of a support system, deviation from support standards and other installation practices will influence the extent of the variation.

The primary spreadsheet of the model can be adapted to accommodate many support installation practices, even those that are not installed to standard. Because of this flexibility, this spreadsheet of the model can be considered the most reliable of the three. The reliability of the results from the executive spreadsheet depends on how comparable the recommended support components are to the components of a predefined support system. The more similar these components are to a particular predefined support system, the more reliable the results are. The executive spreadsheet and the engineer spreadsheet assume that sidewalls and hanging wall are supported uniformly. If this is the case for a given case study, the results will be reliable. Both these spreadsheets assume that the support elements are installed according to standard, if the support components are not installed to standard; it is likely that the support cost will be underestimated or overestimated.

5.1 Summary

The following items were covered in this chapter:

- The analysis of the results indicate that the rehabilitation costs were consistently high in all the case studies.
- When compared to the benchmark costs in case study 1, the spreadsheets are reliable. The primary version gave results closest to the benchmark costs.
- It shows that when the tunnels were supported according to standard, the different spreadsheets estimate similar costs.

6 CHAPTER 6: DISCUSSION

In Chapter 3, an Excel model to quantify consequences of rockbursts was introduced. The model was named the Consequence-Quantifying Model. In Chapter 4, the model was used to quantify, in detail, consequences of four case studies. The case studies illustrated the functionality and applications of the model. In Chapter 2, two types of energy absorbing support systems, suitable for rockburst prone mining environments were discussed. These support systems were applied to the analysed case studies to illustrate the potential value preservation or creation that could have been realised. In this chapter, the different spreadsheets of the consequence-quantifying model are evaluated and the role of the model in determining appropriate support during a risk-based support design process is discussed.

6.1 Consequence Quantifying Model

The primary objective of this research is to develop an Excel model to be used to evaluate consequences of potential rockbursts. The purpose of the consequence-quantifying model is to evaluate financial losses associated rockbursts. There are three different spreadsheets of the model; the first one is the executive spreadsheet. It can be used to give an overview of the costs and/or losses associated with a rockburst event. Second, is the engineer spreadsheet that can be used during support design and financial optimisation of support systems. This spreadsheet assumes that support elements were installed according to rock engineering support standards and the recommended design parameters. The engineer spreadsheet can facilitate financial optimisation of different support systems before a final decision is made on the choice of support for a given tunnel in a particular mining environment. Lastly is the primary spreadsheet, which evaluates costs of support as installed in the tunnel and does not assume that support was installed according to recommended support standards. This spreadsheet is comprehensive and can facilitate back analysis of losses after a rockburst event.

6.1.1 Executive spreadsheet

The executive spreadsheet is the most time efficient of all the spreadsheets as it gives an overview of the estimated loss, based on a predefined support system. This spreadsheet does not require the user to have extensive technical knowledge. Because of this, it is better suited for executive level management. It can help give a brief overview of the risk profile and potential loss associated with rockbursts and the costs of the possible support systems.

The executive spreadsheet often gives the highest financial loss estimates when compared to the other spreadsheets. This is evident when the damaged or recommended support units deviate significantly from any of the components of the different predefined support systems described in Table 3-3. When the support units in the case study are fewer than components of the nearest support system such as in Case study 3, the executive spreadsheet overestimates the financial loss. If a case study has a mixture of both yielding and static support units, choosing a support system can be a challenge and may result in overestimated or underestimated support costs. This discrepancy can be eliminated by installing support according to predefined standards.

6.1.2 Engineer spreadsheet

The engineer spreadsheet assumes that the support components are installed according to rock engineering support standards and recommendations. In cases where the support units are not installed to the current support standards, the costs may be under or overestimated. This spreadsheet assumes that all the walls (sidewalls and roof) of the tunnel are supported in similar manner. This assumption is challenged when not all the walls are supported in a similar manner. In such cases, the model overestimates or underestimates the costs. The engineer can use this spreadsheet of the model to design and financially optimise support systems. The support units are assumed to be installed according to the current support standards.

6.1.3 Primary spreadsheet

The primary spreadsheet can be adapted to suit any variation in support installation practices. This includes support not installed according to current support standards, cases where variations of the same support type (e.g. tendons: ripple bars, splitset and durabars) are installed successively along the same linear metres and in cases where not all walls are supported the same. The primary spreadsheet will yield the most accurate results of all the spreadsheets due to its adaptability to any support installation practices. This version of the model can be used for back analysis after an event has occurred.

The primary spreadsheet is the superior model in terms of accuracy and the extent of detail that can be included in the evaluation. It is easily adaptable to suit different support conditions and support installation practices. The engineer spreadsheet is suitable for scenarios where all sidewalls and roof are affected and are all rehabilitated in a similar manner; and where the support units are installed according to the mine's support standards. It can be used during the support design process to optimise cost of a support system. The executive spreadsheet is suitable for performing an overview of the support systems required, but it is the most important outcome of this research due to its intended users.

The goal is to encourage executive level management to reconsider their current support design principles and support design procedure. The executive spreadsheet provides a starting point for risk based support design for a rockbursting mining environment. Once the executives have an overview of cost implications of each support system, and the potential for financial gain if an appropriate support system is implemented, they could request a detailed support review and analysis from the technical staff. This research is aimed at developing a different approach to support installation and to encourage a proactive culture instead of the current reactive culture

6.2 Expansive implications of case study results

The case studies have focussed on the immediate area around which a rockburst has occurred. However, in reality, yielding support would have been installed over a greater area or over a longer length of the tunnel; hence costs would have been higher and considered unfavourable due to their costs when compared to rigid support systems. The initial cost of energy absorbing support systems is the reason some South African mines are discouraged from diligent implementation of these support systems, as the cost of yielding tendons is much higher than the cost of rigid support. Ortlepp (1994) has indicated that these costs can be reduced by increasing the spacing between the tendons. However, the increased spacing can result in rock falls between the tendons, which will be alleviated by the usage chain-link mesh with lacing.

Table 5 1 shows what different support units will cost a mine over a 100 m length of a 3.7 m by 3.7 m tunnel. This table is adapted from work by Ortlepp (1994) and Ortlepp & Stacey (1995) on the relationship between tendon spacing and support cost. Each tendon is required to absorb 20 kJ of energy, thus, for a cubic metre block, 80 kN of force over an assumed 0.25 m displacement, the allowed rock mass displacement before the support can fully stop the movement (Ortlepp, 1994). The peak loads of each tendon are based on their specifications and Figure 2-9, the costs of cone bolts are assumed, while the costs of other tendons are from the mines' material catalogue.

$$\text{Required force} = \frac{Energy\ to\ be\ absorbed}{Displacement} \quad (5.1)$$

$$= \frac{20\ kJ}{0.25\ m}$$

$$= 80\ \text{kN}$$

$$\text{Tendon spacing} = \sqrt{\frac{Tendon\ Peak\ Load}{Force\ Required}} \quad (5.2)$$

$$\text{Number of tendons per ring} = \frac{2 \times tunnel\ hight + tunnel\ width}{Bolt\ spacing} + 1 \quad (5.3)$$

Number of tendons over span = $\left(\frac{span}{spacing}+1\right)\times number\ of\ tendons\ per\ ring$ 5.4

Cost of tendons over given span = Number of tendons over span × unit price 5.5

Table 6-1: Costs of different tendons over a 100 m tunnel length

Assumptions						
Support Distance	100 m					
Tunnel Height	3.7 m					
Tunnel Width	3.7 m					
Rock Mass Displacement	0.25 m					
Force Required	80 kN					
Tendon	Peak Load	Unit Price	Spacing	Tendons per Row	Total Tendons	Total Cost
Splitset 39mm 2.2m	50 kN	R 78.76	0.79 m	15	1918	R 151 024.79
Cone bolt 16mm 2.2m	170 kN	R 98.12	1.46 m	9	600	R 58 829.51
Durabar 16mm 2.2m	150 kN	R 98.12	1.37 m	9	674	R 66 146.22
Rebar 16mm 2.2m	200 kN	R 75.25	1.58 m	8	515	R 38 773.75
Mphondo bolt 16mm 2.1m	80 kN	R 81.45	1.00 m	12	1222	R 99 540.05
Cone bolt 22mm 2.2m	200 kN	R 132.01	1.58 m	8	515	R 68 020.24

5.5

Table 6-1 shows that the commonly used 39 mm splitset is more expensive than 16 mm Durabar, the yielding tendon available in South Africa. The table also indicates that at 50 kN peak load, the 11 tendons used at the mines is inadequate, although using only 11 tendons reduces the cost of tendons to R 86 038.43 over 100 m tunnel length. Although the table shows that rebar tendons would be cheaper, Figure 2-9 shows that they are not suitable for dynamic environments as they fail after only 50 mm extension when subjected to a pull load. The table shows that a 16 mm 2.2 m long cone bolt is the cheapest over the 100 m tunnel span and the 16 mm Durabar is the second best option. This indicates that the financial value that can be created by a Durabar or a cone bolt is far higher the perceived financial benefit of using splitsets, this was also indicated by the case studies.

6.3 Value creation as a support design parameter

During a seismic event, of the following can occur: either the support will fail to contain the dynamic loading to which it is subjected and the support and rock mass at the periphery of the tunnel will fail; or the support system can successfully contain the rockburst. In the event that the seismic event is successfully contained and the access tunnel is still required, value loss was prevented. In the event that the support systems fails and the tunnel has reached its end of life, there is no financial loss. In the event that the support has failed but the tunnel is still required, financial value is lost. The lost value refers to the initial cost of the failed support, the cost of reopening the tunnel, the loss of production associated with the tunnel and the personnel casualties.

Quantified potential consequences give an indication of the potential financial value that could either be preserved, created or destroyed depending on the mine design layout and the support system in place. Assuming that mine layout considered the potential seismicity of the mine, the preservation and creation of value depends significantly on the choice of support system.

Designing support for seismically active mines should be viewed as a risk management strategy. The process should start with an optimum choice of mine layout design and adequate support system. The choice of support system should be an outcome of a risk based support design (using tools such as the risk matrix and considering the magnitude of potential consequences of rockbursts) with an intention of creating and preserving value of the operation by enhancing the stability of excavations. The role of quantifying consequences is shown as a potential input parameter in risk based support design for access tunnels in seismically active mines. Designing for rockbursts, as a risk, will greatly influence the choice of support. The outcome would be support design with the intention of value preservation and creation in rockburst prone mining environments.

6.4 Risk-Based Support Design

In this section, quantified–consequences and suitable energy absorbing support systems are reviewed, as a strategy for managing rockburst risk in mining environments prone to seismicity. A risk matrix can be used to classify the severity of a potential rockburst event. The juncture at which the probability of occurrence of a rockburst and the magnitude of the consequences meet is the risk classification. The limits of a risk classification are influenced by stakeholder risk appetite. The risk classifications of the risk matrix will influence the support system required to minimise or prevent the impact of the rockbursts.

Since the magnitude of a rockburst or a seismic event cannot be estimated, therefore the magnitude of potential loss should be conservative and guided by historical data and experience. The risk appetite of stakeholders, mining environment and magnitude of potential loss should influence what is defined as conservative. An example of an outline of a stakeholder risk appetite is the risk matrix shown in Figure 2-5. Figure 3-4 shows that less than four percent of seismic events resulted in rockbursts in tunnels at Mine Y; this can be used as the probability of failure while magnitude of potential loss can be estimated with the consequence-quantifying model.

For a support system to be effective, its energy absorption capacity should be greater than the kinetic energy generated by the rock mass that the support system is intended to retain (Erasmus, et al., 2009). However, the challenge is that the magnitude of the kinetic energy released during a rockburst cannot be anticipated accurately and the failure mechanisms are complex to anticipate (Stacey, 2013). Rockbursts are unpredictable events that are not yet fully understood. This lack of understanding in behaviour of rockbursts makes it a challenge to anticipate rockbursts with precision and to design support according to energy demand. In an effort to increase the energy carrying capacity of the support system, there is a possibility of overdesigning. This is a challenge that may not be truly overcome, as there are too many uncertainties. In dynamic loading conditions, it may be better to be conservative and overdesign than to under design, and to use the best suitable support systems for the given environment.

The design of the support should be informed by the magnitude of risk that a mine is willing to incur. The magnitude of consequences associated with rockbursts and the risk matrix can inform this decision. The amount of financial consequential loss is the potential value gain from appropriate energy absorbing support regardless of the perceived high cost compared to rigid support systems. The “extra” cost of an energy absorbing support system is worth it and can create the financial benefit of reducing financial consequences of rockbursts and reduce the number of casualties at the work place. This will result in improved stakeholder relations thus maximising value.

6.5 Summary

In this chapter, the different spreadsheets were discussed. Executive level management can use the executive spreadsheet to give an overview of the financial loss and potential financial gain associated with adequate support systems, they can then ask for a detailed support analysis from technical staff. This spreadsheet will facilitate proactive rockburst risk management among mine executives. Considering the energy absorption properties, the peak load and extension distance before failure, the inter-ring and intra-ring tendon spacing can be increased, thus significantly reducing the costs without compromising the energy absorbing properties of the support system. Reduced costs will aid in diligent installation of appropriate support for a given environment, thus preserving or creating value, which would have otherwise been lost due to perceived cheaper rigid support. Value creation would be a primary goal for support design, thus catering for rockburst risk.

The goal is to facilitate risk based support design that will have employee safety, value-creation and reduced financial consequences as the primary goals. This will result in improved rockburst risk management and a more proactive support design and rockburst risk management from executive level management. This proactive measure will facilitate diligent installation of energy-absorbing support systems in seismically active underground excavations.

7 CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS

The prospect of increasing value can motivate change. Highlighting the magnitude of financial loss associated with rockbursts may help improve productivity and personnel safety. It may lead to proactive measures to improve stability of access tunnels by using support systems more suitable for seismically active deep level gold mining environments in an effort to reduce financial loss.

7.1 Rockburst as a Risk

Rockburst risk is a function of the probability of occurrence of a rockburst event and magnitude of the consequences of the rockburst event. There is no clear relationship between the magnitude of a seismic event and the extent of a rockburst damage although seismic events with a high local magnitude often result in significant damage and vice versa. A high M_L magnitude of a seismic event does not automatically translate to extensive rockburst damage or greater loss. The magnitude of rockburst damage is influenced by the geology, seismic history, mine design layout and the support systems in place. The probability of experiencing a rockburst or its magnitude cannot be accurately anticipated at this stage. However, in South Africa, seismicity and the resulting rockbursts are prevalent in deep level mining with an average of 73% of recorded mining related seismic events occurring in the Witwatersrand basin (Council for Geoscience, 2016). Seismic data recorded at Mine Y showed that less than 4% of seismic events recorded in a year resulted in rockburst damage in access tunnels. Given the above Council for Geoscience information, the probability of experiencing a rockburst event is relatively (unquantifiably) higher in a Witwatersrand gold mine than in other mining areas due to the extent and depth of mining. It is better to anticipate a rockburst event at any given time in such environments. Energy absorbing support systems can be used to manage the anticipated rockbursts. These support systems have the capacity to yield and deform under dynamic loading while containing the deformed rock mass on the periphery of the excavation.

7.2 Indirect Rockburst Consequences

Quantifying the magnitude of rockburst damage is one of the objectives of this research. The focus is on quantifying indirect consequences of rockbursts in mining environments experiencing dynamic loading. Indirect consequences were classified into the following groups:

- Personnel casualties: these include dressing cases, lost time injuries, serious injuries and fatalities due to rockbursts.
- Support costs: these include costs of support components that failed during a rockburst event and costs of support units that were used to rehabilitate the damage.
- Revenue losses: these are production time and tonnage lost, and Section 54 stoppages directly affecting production and ore movement.
- New access development: these costs account for explosives and consumables required to develop and support a new tunnel to bypass a damaged tunnel. Labour costs are considered as part of overhead cost and are not considered in these case studies unless stated that a private contractor had to be hired to perform a task, which will be an additional cost to the mine.

7.3 The Consequence-Quantifying Model

The consequence-quantifying model is used to quantify the indirect financial consequence of rockbursts. The model that was developed as part of the research has three different versions, namely the primary, the engineer and the executive spreadsheets. The three versions of the model were applied to four case studies, the results from which were evaluated. It was concluded that the primary spreadsheet is the most reliable of the three.

- From the first case study, the primary spreadsheet is the most accurate of the three versions.

- The primary spreadsheet is easily adaptable to suit different support installation practices. Due to its flexibility, it can be used for back analysis after a rockburst event. Executives can then require their technical staff to provide them with a more detailed information from the primary spreadsheet, so that they can make better informed decisions.
- The engineer spreadsheet can be used to optimise costs of support during support design. The model assumes that the support is installed according to the prescribed tunnel support standards.
- An individual with limited technical knowledge can use the executive spreadsheet, and it is therefore appropriate for use by mining executives. The spreadsheet gives an overview of support costs and estimated financial loss, and hence the value that that can be created by implementing energy absorbing support systems. The accuracy of the model increases when support units of interest are similar to the components of predefined support systems. Each operation can define its own support systems according to their rock engineering requirements and standards.

7.4 Mitigating Rockburst Risk

Sequential grid mining is commonly practised in seismically active mines, in order to reduce impacts of mining induced seismicity. The mining method does not leave abutments or remnants and the back area is back-filled in order to control closure and reduce exposed open excavations. In a sequential grid mine, the panels are mined towards a solid and away from geological features. Effective rockburst management considers the geology, the seismic history, the mine layout and the support requirements. Support is the last line of defence in managing rockburst risk. Energy absorbing support systems are suitable for environments that experience dynamic stress changes. Three support systems were considered in this research:

- Rigid support system: Suitable for shallower mining environments that are subjected to static loading. The system comprises of rigid tendons, long anchors, weld mesh and shotcrete.

- Yielding support system: A support system that has energy absorbing capabilities and is suitable for excavations subjected to frequent dynamic stress changes such as seismic events. This system comprises of yielding tendons, long anchors, diamond mesh with lacing and thin spray-on liner.
- Yielding set support system: This is a system suitable for high-risk access tunnels, which provide the only access to panels or a main access to multiple other tunnels. The system comprises of yielding tendons, long anchors, chain-link mesh with lacing and yielding sets with foamcrete.
- A variation of the yielding set system is the I-Beam set system. It is considered to be a less expensive version of the yielding set support system. The most common I-Beam system among the case studies comprises of rigid tendons, long anchors, I-Beams, elongates or pipe sets, lagging and foamcrete.

7.5 Value

Value is the amount of money that has been saved because an appropriate support system was able to contain a seismic event, thus minimising the impact of the associated rockburst. Suitable energy absorbing support systems are more likely to contain a rockburst event and prevent value loss.

- A large number of rockbursts are expected in deep Wits mines, with dykes and faults being high-risk areas.
- Energy absorbing support systems provide better support in seismically active mining environments than rigid support systems.
- It costs R 7 500 /m and R 3 600 /m respectively to install a yielding and rigid support system. In the observed case studies, all the failed tunnels were supported with rigid support.
- It costs R 21 300 /m and R 7 800 /m respectively to install yielding sets and I-beam sets.
- Increasing the spacing between yielding tendons will significantly reduce the cost of energy absorbing support systems.

- For every reef blast that a crew misses due to a blocked access or panel unavailability, the operation loses R 126 500, 00 per day per crew.
- Of the consequences studied in this research, interrupted ore flow is the biggest source of financial loss when a rockburst occurs in an access tunnel leading to operational panels.
- In the likely event of a rockburst, the benefits of relatively costly yielding support systems far outweigh the benefits of less costly static support units, as shown in Chapter 5. Cutting costs by minimising support does not benefit the operation in the event of rockburst damage. Witwatersrand mines experience frequent dynamic stress changes, and therefore support systems, which can yield under dynamic loading, are essential.
- The possible financial consequences and the percentage of seismic events that result in rockbursts at a specific mine can be used to quantify the potential risk.
- Management can use a risk matrix to determine the classification of the potential consequences. The classifications on the risk matrix will be influenced by the stakeholder risk appetite, which is in-turn informed by/should be informed by the mining environment or similar criteria.
- The research that has been described in this dissertation has shown that by installing yielding support systems to contain rockburst damage, significant value can be created for the mining operation.

7.6 Recommendations

- Diligent installation of a yielding support system in rockburst prone mines, especially in areas with a significant number of geological structures or in locations with known seismically active geological structures
- Using the magnitude of possible financial loss in the event of a rockburst and the risk appetite, to inform the type of support systems to be used in environments under dynamic loading.
- Using value preservation and creation, as a criterion for support selection during a risk based support design, for environments prone to rockburst events.

- Increase the spacing between yielding tendons based on energy absorbing properties of the tendon. This will reduce the cost of tendons therefore of energy absorbing support systems without compromising the integrity of the support system.
- Consider furthering the research by looking at the time value of money. To see the long term effects of loss associated with rockbursts in tunnels.
- This study uses the benefit of hindsight to quantify losses, it should be considered to study tunnels before failure.
- The spreadsheets of this consequence quantifying tool can be improved and be developed more with experience and regular use.
- Additional data, and increasing the number of case studies that were analysed in detail, would have improved the understanding of the impact of the different support systems.

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9 APPENDIX

Table 9-1: Details of collected rockbursts in access tunnels

Case Study	Year	Types	Location	Geological Features	Magnitude	Volume	Line Metres	Damage location	Impacts	Support	Other
CS1	2004	Strainburst	Haulage	lava and Quartzite	1.6	145.6	35	Both sw	Affected 109_52_E_Top	Substandard mesh and lacing, long anchors; Protruding tendons after damage	
CS2	2004	Slip	Cross cut	Lava, three dykes	0.5	13	13	Sw and hw shakedown		Unequally spaced split sets; Corroded support, and over break and protruding support	Three other seismic events in the vicinity
CS3	2005	Strainburst	Cross cut	Quartzite, Little Tumi Dyke		22.32	9.3	HW	Interrupted tramming	Rusted support, >10cm protruding tendons	
CS4	2007	Strainburst	Cross cut	Quartzite, Georgette Dyke, multiple other dykes and a fault		0	0	face and side wall contact, dev end	People removed	Gunnite, koepe ropes where xcut intersect Georgette	
CS5	2008	Rockburst	Cross cut	Joint sets		14.7	7			Damaged all split sets in area, gunite	
CS6	2009	Rockburst	Decline	Lesser Green Dyke	0.6	30	12.5	SW		Split sets not suitable and dyke intersection	
CS7	2009	Rockburst	Cross cut	Open Dyke	2.8	31.07	41	Both sw		Tendons at poor angle, corroded due to moisture from above workings, gunite failed due to moisture and no secondary support	
CS8	2009	Rockburst	Haulage	Lesser Green Dyke	0.2 +0.9	40.67	17	Western SW		Some failed tendons which were installed to old standards and insufficient areal support thus failure between tendons	In vicinity of multiple previous seismic events; break made inside the Lesser Green Dyke(Bull nose)
CS9	2010	Strainburst	Cross cut		2.3	0.168	0.8	HW	1 Fatal	2.1m Split sets, Elongates, Timber composite packs; Secondary: Wire mesh and lacing, Ferrule loops, Tendons consisting of 3.6m koepe ropes, Gunite, pipe sets with void fill	Bull nose, Reef intersection
CS10	2010	Slip	Cross cut		2.4	2.8	20	Both sw		Rusted spit sets, hot humid RAW	Source in a panel close to two faults, damage in Cross cut, two >2 ML events in last three months
CS11	2010	Slip	Haulage	Greater Green Dyke	2.9	204	20	Both sw	Personnel withdrawn	Rippled bar, wire mesh and lacing	
CS12	2010	Slip	Haulage	DD dyke	-0.6	5	5.5	South SW	Three injuries	late installation of secondary support, failed TSL	Damage increases towards face

CS13	2011	Strainburst	Haulage	Georgette Dyke	-0.2	6.336	14.6	SW and holing face	Three LTI and ACC	Split sets, welded mesh, koepe ropes and camlock jacks	Last mined over a year ago.
CS14	2013	Slip	Travelling way	PE Dyke, two joints	2.1	Access blocked				Substandard support and lack of secondary support in the form of mesh and lacing	Access was never reopened
CS15	2013	Slip	Cross cut	Dougie Dyke and 3 joint sets	>1	9.625	8.7	SW		Failed Gunite, tension failed Shepard Crooks, Dislodged Rocprops	Reef intersection
CS16	2015	Strainburst	Haulage	Quartzite, Georgette Dyke	0.3 and 0.5	23.9068	17.8	Both sw + Shakedown in workshop + escape route		Corroded split sets, weld mesh. ; Mechanical long anchors	Shake down by the escape, route near Lesser Green
CS17	2016	Slip	Cross cut	Lava, Thin white dyke and Disappearing dyke	0.4, 0.1		25 on W sw and 31.9 on E sw	Both SW		Rusted tendons, RSJ's and Pipe sets, and damaged steel reinforced wetcrete.	Reef intersection
CS18	2016	Strainburst	Haulage			0.104	1			Corroded rock studs, damaged old weld mesh, not long anchors(secondary support), Shotcrete sprayed on hw and sw's	Water dripping from hw, support not to standard, start-up risk assessment not done
CS19	2015	Rockburst	Haulage	Thin shale layers with feldspar and quartz veins, Near Bank dyke	2.8	0.955	1.4	Face		Mphondo Bars and welded mesh not overlapping, Long anchors	One SI
CS20	2015	Rockburst	Travelling way		1.3	170	50	North sidewall			
CS21	2015	Rockburst	Travelling way	C-S dyke, two faults	1.6	16.8	7			Durabars, Appolo packs, wedge prop elongates, RSJ beams, welded mesh	Stope failure, increased panel lengths and thus higher stress build up
CS22	2015	Rockburst	Haulage	C-S dyke	2.5	12.6	10	FW,		Weld mesh, Mphondo bolts, Durabars, Long anchors, RSJ beams with cribbing and voidfill	To replace 31m of railing; Near a mined out area (last mined 2014), i.e. high abutment stress
CS23	2015	Rockburst	Cross cut	C-S dyke	2.5, 1.6,0.4,1.5,0.6,0.6,0.8	135	15	both SW		Weld mesh, Mphondo bolts, Durabars, Long anchors, RSJ beams with cribbing and voidfill	Failed RSJ sets
CS24	2015	Rockburst	Cross cut	C-S dyke	1.9	35.3	5.7			Long anchors, durabars, Mphondo bolts, weld mesh, no lacing, Post gunite	Prevented access further access into tunnel
CS25	2015	Rockburst	Haulage	Brazil dyke	0.2	22.5	52	52m north SW		Mphondo bolts, Durabars, welded mesh, long anchors (koepe ropes)	2 SI and 1 Fatal
CS26	2014	Rockburst	Haulage	C-S dyke	1.7	19.845	21	FW		Mphondo Bars, mechanical anchors, welded mesh, lacing and RSJ (as sets) and voidfill	Source and damage location not the same
CS27	2013	Rockburst	Haulage	Christo fault, Dyke	2.8,1.6,1.3	3.45	23	FW		Rock studs, Shepard crooks, welded mesh and lacing, End anchored cable anchors; damaged mesh and lacing	Rock fall between tendons

CS28	2013	Rockburst	Haulage	Greenbar (weak rock), Ken Dyke	1.4,3.4,0.7	24.48	17.2			Mesh and Lacing, TSL, Shotcrete, Long anchors, RSJ and ring sets; Corroded mesh and lace, LA	
CS29	2012	Strainburst	Haulage	13 m after Soll Dyke		3.624	8	SW		Welded mesh intact, manged to contain the burst, will be stripped and redone. To install welded mesh, long anchors, gunite	Lost night and day shits development
CS30	2012	Strainburst	Cross cut	C-S Dyke			11.5	HW, SW		Welded mesh and lacing,	Recommended, weld mesh, lacing gunite, long anchors, Durabars
CS31	2012		Haulage	Friday and Skelm dykes	1.6,0.5	110	52	Right sidewall	2 SI and 1 Fatal	2.1m Mpondo bolts, Welded mesh, Koepe robes and lacing	Busy installing Durabars
CS32	2011	Strainburst	Haulage	Friday Dyke		0.02625	0.35	Right sidewall			
CS33	2011	Rockburst	Haulage	Pretorius Fault Zone	1	75	25		One SI	Durabars, 4 mm tunnel guard, 3.6m long anchors; no Mesh and lacing yet	
CS34	2011	Strainburst	Haulage	Pretorius fault zones		3.15	3		I LTI	Durabars, tunnel guard	
CS35	2011	Rockburst	Haulage	Bank Dyke(3.2) Speckled (2.4)	3.2	795	70		Closure of 104-88 N & S panel closure	Durabars, Pre gunite, mesh and lacing, posy gunite, long anchors, I-Beam sets	
CS36	2011	Rockburst	Haulage				12	South SW			
CS37	2010	Strainburst	Haulage	Pretorius Fault Zone	-0.1						
CS38	2010	Strainburst	Haulage			0.003	0.2	Southern SW	one LTI	Durabars only	
CS39	2010	Strainburst	Haulage	Friday Dyke						Splitsets, weld mesh	
CS40	2010	Strainburst	Haulage	Shale, Brazil dyke		0.041	0.6		one LTI	Durabars only	
CS41	2010	Rockburst	Haulage	Friday dyke	1	132	22	both SW		Durabars only	
CS42	2010	Rockburst	Haulage	Speckled dyke, two intrusions	1						
CS43	2010	Strainburst	Haulage	Joint			1.8	Eastern SW			
CS44	2009	Strainburst	Haulage	Jeppestown shale				Face	One LTI		
CS45	2009	Strainburst	Haulage	Peggy dyke, Pretorius fault Zones				Face and Both SW	One injured	Recommended: Durabars,	
CS46	2009	Strainburst	Cross cut	Faults and dykes				Western SW	One LTI	Smooth bar at 1.3 m square pattern	
CS47	2009	Rockburst	Cross cut	Joint set	1.2, 1.9			Eastern SW	Completely closed connecting xcut	Shepard Crooks, 2.3 m Durabars	
CS48	2009	Strainburst	Haulage						One injured		
CS49	2008	Rockburst	Haulage		1.3			FW		RSJ and concrete slap for shuttering(i.e. laggings); Recommended: Mesh and lacing, RSJ sets and voidfill,	
CS50	2007	Rockburst	Cross cut	Dyke	2.3			HW and SW	Total closure		
CS51	2005	Rockburst	Cross cut	Maraisburg Quartzite, Fault	1.5					Recommended: RSJ sets and voidfill	
CS52	2004	Rockburst	Haulage					HW		Pulled out durabars	

9.1 Executive Spreadsheet

Table 9-2: Input interface for case study 1 using executive spreadsheet

Damage			
Line metres	*m*	*32*	
Tunnel height	*m*	*3.7*	
Tunnel width	*m*	*3.7*	
Personnel casualties			***R 0.00***
Hospitalised <14 days	*number of cases*	*0*	*R 0.00*
Hospitalised >14 days	*number of cases*	*0*	*R 0.00*
Fatalities	*number of cases*	*0*	*R 0.00*
Original support system			***R 292 794.71***
	Choose support system present at damage area	*I-Beam set support system*	*R 292 794.71*
Revenue loss			***R 5692 500.00***
Number of crews affected	*crews*	*3*	
Average weekly production	*t per week per crew*	*110*	
Grade	*g/t*	*10*	
Time crew spent standing	*in weeks*	*3*	
Price	*R/kg*	*575000*	
Is raise line or tunnel accessible?	*Yes or No*	*yes*	
If no, remaining tonnes of reef	*t*		
Remedial course of action			***R 0.00***
New access	*Yes or No*	*no*	
If yes, line metres	*m*		
Rehabilitation	*Yes or No*	*yes*	
If yes, average additional line metres on either side	*m*	*5*	
Abandoned	*Yes or No*	*no*	
New rehabilitation metres	*m*	*42*	
Remedial support system			***R 384 293.06***
	Choose support system recommended for rehabilitation	*I-Beam set support system*	*R 384 293.06*

Table 9-3: Input interface for case study 2 using executive spreadsheet

	Units	Data Input	Cost
Damage			
Line metres	m	5	
Tunnel height	m	3.7	
Tunnel width	m	4.5	
Personnel Safety			**R 1 914 000.00**
Lost Time<14 days	number of cases	1	R 202 000.00
Lost time>14 days	number of cases	1	R 212 000.00
Number of fatalities	number of cases	1	R 1 500 000.00
Original Support System			**R 21 735.55**
	Choose support system present at damage area	Static support system	R 21 735.55
Revenue Loss			**R -**
Number of crews affected	crews		
Average weekly production	t per week per crew		
Grade	g/t		
Time crew spent standing	in weeks		
Price	R/kg		
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial Action			**R -**
New access	Yes or No	no	
If yes, line metres	m	0	
Rehabilitation	Yes or No	yes	
If yes, average additional line metres on either side	m	5	
Abandoned	Yes or No	no	
New rehabilitation metres	m	15	
Remedial Support System			**R 65 206.64**
	Choose support system recommended for rehabilitation	Static support system	R 65 206.64

Table 9-4: Input interface for case study 3 using executive spreadsheet

	Units	Data Input	Cost
Damage			
Line metres	m	41	
Tunnel height	m	3.7	
Tunnel width	m	3.7	
Personnel casualties			**R -**
Hospitalised <14 days	number of cases	0	R -
Hospitalised >14 days	number of cases	0	R -
Fatalities	number of cases	0	R -
Original support system			**R 147 069.50**
	Choose support system present at damage area	Static support system	R 147 069.50
Revenue loss			**R 5 692 500.00**
Number of crews affected	crews	3	
Average weekly production	t per week per crew	110	
Grade	g/t	10	
Time crew spent standing	in weeks	3	
Price	R/kg	575000	
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial course of action			**R 244 644.81**
New access	Yes or No	yes	
If yes, line metres	m	315	
Rehabilitation	Yes or No	no	
If yes, average additional line metres on either side	m	0	
Abandoned	Yes or No	no	
New rehabilitation metres	m	315	
Remedial support system			**R 1 129 924.22**
	Choose support system recommended for rehabilitation	Static support system	R 1 129 924.22

Table 9-5: Input interface for case study 4 using executive spreadsheet

	Units	Data Input	Cost
Damage			
Line metres	m	8.00	
Tunnel height	m	2.00	
Tunnel width	m	2.80	
Personnel Safety			**R 0.00**
Lost Time<14 days	number of cases	0.00	R 0.00
Lost time>14 days	number of cases	0.00	R 0.00
Number of fatalities	number of cases	0.00	R 0.00
Original Support System			**R 44 134.77**
	Choose support system present at damage area	Static support system	R 12 278.91
		Timber packs	R 31 855.86
Revenue Loss			**R 1 897 500.00**
Number of crews affected	crews	3	
Average weekly production	t per week per crew	110	
Grade	g/t	10	
Time crew spent standing	in weeks	1	
Price	R/kg	575000.00	
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial Action			**R 0.00**
New access	Yes or No	no	
If yes, line metres	m	0.00	
Rehabilitation	Yes or No	no	
If yes, average additional line metres on either side	m	0.00	
Abandoned	Yes or No	yes	
New rehabilitation metres	m	0.00	
Remedial Support System			**R 0.00**
	Choose support system recommended for rehabilitation	Static support system	R 0.00

9.2 Engineer Spreadsheet

Table 9-6: Engineer spreadsheet inventory

Support unit	Specific description	Bolt length		Bolt diameter	Hole diameter	Grout density (kg/m3)	Solid content	Mass of grout per bolt	Bolt	Faceplate	Grout cost per kg	Unit cost	Number per row	Inter-raw spacing	Cost per metre advance
Tendons															
Rigid	0.5m splitset	0,5		16	20	1600	77%	0,07	R 19,04	18,88	6,24	R 38,36	11	1	R 21,91
	1.2m splitset	1,2		16	20	1600	77%	0,17	R 46,30	31,63	6,24	R 78,97	11	1	R 868,71
	2.1m splitset	2,1		16	20	1600	77%	0,29	R 43,00	46,3	6,24	R 91,13	11	1	R 1 002,40
	2.2m splitset	2,2		16	20	1600	77%	0,31	R 78,76	0	6,24	R 80,67	11	1	R 887,41
Ripple bar	1.5m KatBar w washer	1,5		16	20	1600	77%	0,21	R 62,66	0	6,24	R 63,97	11	1	R 703,62
	2.2m KatBar w washer	2,2		16	20	1600	77%	0,31	R 75,25	0	6,24	R 77,16	11	1	R 848,80
	2.9m KatBar w washer	2,9		16	20	1600	77%	0,40	R 151,19	0	6,24	R 153,71	11	1	R 1 690,84
	2.9m Unibar w washer	2,9		16	20	1600	77%	0,40	R 124,71	0	6,24	R 127,23	11	1	R 1 399,56
Shepherd Crook	Mphondo Welded shepherd crook w plate	2,1		16	20	1600	77%	0,29	R 81,45	0	6,24	R 83,28	11	1	R 916,05
Yielding	1.5m Debonded Durabar rod	1,5		16	20	1600	77%	0,21	R 46,66		6,24	R 47,96	11	1	R 527,61
	2.2m Fish Hook Durabar assembly bolt washer	2,2		16	20	1600	77%	0,31	R 103,74	0	6,24	R 105,65	11	1	R 1 162,19
	2.2m Durabar+Top hat+150mm washer	2,2		16	20	1600	77%	0,31	R 98,12	0	6,24	R 100,03	11	1	R 1 100,37
	2.2m Durabar+Top hat+200mm washer	2,2		16	20	1600	77%	0,31	R 98,12	0	6,24	R 100,03	11	1	R 1 100,37
	2.2m Par1 Yield bolt System w washer	2,2		20	20	1600	77%	0,00	R 300,47	0	6,24	R 300,47	11	1	R 3 305,17
Straps	Square durastrap	1,2							R 168,08		6,244	R 168,08	9,92	9,92	R 168,08
Long anchors															
Cable anchors	4.5m Surelock flexible anchor assembly	4,5		16	20	1600	77%	0,63	R 286,06		6,244	R 289,98	9	2	R 1 304,89
	3.6m M&J 25 ton cable anchor	3,6		16	20	1600	77%	0,50	R 67,00		6,244	R 70,13	9	2	R 315,59
	3.5m absolute mechanical anchor assembly	3,5		16	20	1600	77%	0,49	R 260,93		6,244	R 263,98	9	2	R 1 187,89
	4.1m absolute mechanical anchor assembly	4,1		16	20	1600	77%	0,57	R 289,00		6,244	R 292,57	9	2	R 1 316,55
	4.5m absolute mechanical anchor assembly	4,5		16	20	1600	77%	0,63	R 622,80		6,244	R 626,72	9	2	R 2 820,22
	6.5m absolute mechanical anchor assembly	6,5		16	20	1600	77%	0,91	R 737,31		6,244	R 742,97	9	2	R 3 343,34
	Specific description	Length		Width					Mesh			Cost per square metre	Mesh width	Inter-raw spacing	Cost per metre advance
Areal															
Weld mesh	Galv Mesh Ms Mw-1.3x1.3x5.6	1,3		1,3					R 129,27			R 76,49	11,9	1	R 910,24
	1.7x1.7mx5.6x100x100 Welded Mesh(2 Shts)	1,7		1,7					R 199,11			R 68,90	11,9	1	R 819,86
	Mesh Ms 1.8mx1.2mx5.6mmx100x100mm	1,8		1,2					R 137,79			R 63,79	11,9	1	R 759,12

	Mesh Ms Sets 2.3mx1.3mx5.6x100x100mm	2,3		1,3					R 129,07			R 43,17	11,9	1	R 513,69
	Mesh Ms 2.4mx1.3mx5.6mmx100x100mm	2,4		1,3					R573,72			R 183,88	11,9	1	R 2 188,23
	Mesh Ms 2.5mx1.3mx5.6mmx100x100mm	2,5		1,3					R 235,13			R 72,35	11,9	1	R 860,94
	2.4mx100mmsq X9.5m Lg Roll Ms Galv Mesh	9,5		2,4					R1351,52			R 59,28	11,9	1	R 705,40
	2.4mx100mm Sq X11m Lg Roll Ms Galv Mesh	11		2,4					R100,89			R 53,06	11,9	1	R 631,46
	Mesh Ms 11mx100mmx100mmx2.4mx4.0mm Pn402	11		2,4					R1 71,29			R 63,31	11,9	1	R 753,35
	Weldmesh Ms 20x2,4x3,15x100x100mm Black	20		2,4					R1066,27			R 22,21	11,9	1	R 264,35
												Cost per metre			
Binder Spiral	1m X 5.6mm Galvanised Welded Mesh Spiral	1							R 8,68			R 8,68	11,9	1	R 103,29
													Mesh width	Inter-raw spacing	Cost per metre advance
Chain-link mesh	100x2400x4mmx15m Compacted Diamond Mesh	15		2,4					R 772,58			21,46	11,9	1	R 255,38
	75x1800x3,15mmx15m Diamond Mesh	15		1,8					R 673,80			24,96	11,9	1	R 296,97
												Cost per metre	Inter row total length	Intra-raw tot length	Cost per metre advance
Lacing	15 -20mmx30m Split Lacing Rope Ex Aga	30							R 56,10			R 1,87	11,9	1	R 22,25
	8 -13mmx30m Intact Lacing Rope Ex Aga	30							R 183,75			R 6,13	11,9	1	R 72,89
	8 -13mmx30m Intact Lacing Rope New	30							R 206,62			R 6,89	11,9	1	R 81,96
	8 -13mmx30m Intact Lacing Rope Non Aga	30							R 175,00			R 5,83	11,9	1	R 69,42
	Specific Description	Size (Kg)		Application thickness mm	Application area square m	density	Solid content	Mass of shotcrete	Shotcrete bag			Cost per m2	Application width	Application thickness	Cost per metre advance
Skin support	-														
Shotcrete															
Drycrete	25MPA Semi Dry Drycrete	30		10	1		86%	20,83	R 20,31			R 14,10	11,9	50	R 839,20
	25mpa Drycrete 50x30kg Bags In B/Dis Bag	30		10	1		86%	20,83	R 17,87			R 12,41	11,9	50	R 738,38
	25mpa S/Dry Drycrete 48x30kg Bgs/Bulk Bg	30		10	1		86%	20,83	R 19,72			R 13,69	11,9	50	R 814,82
	Ready Mix, Shotcrete:30 Kg;50; 50x30kg	30		10	1		86%	20,83	R 18,72			R 13,00	11,9	50	R 773,50

Wetcrete	40mpa Ce40 & Oxy Fibre Wetcrete 30kg Bag	30		10	1		86%	20,83	R 29,68			R 20,61	11,9	50	R 1 226,36
	40mpa Bulk Mix Wetcrete 650kg Bulk Bag	650		10	1		86%	20,83	R 454,12			R 14,56	11,9	50	R 866,03
	55xsav30 N/F Wetcrete 30kg 48/Pallet	30		10	1		86%	20,83	R 31,70			R 22,01	11,9	50	R 1 309,83
						density	percentage air	Mass of foamcrete					Set diameter metres	volume	Cost per metre advance
Foamcrete	Xp500 Foamcrete 50x25kg Bags/Bulk Bag	25		1	1	500	0,6	300	R 63,03			R 756,36	3,5	7,028872498	R 5 316,36
				Application thickness mm	Application area square m		Solid content	Mass per m2 @1mm thickness	unit cost			Cost per m2@1mm thickness	application width	Application thickness	Cost per metre advance
Thin spray liner	12,5kg Tunnelguard Thin Spray Skin Liner Additive	12,5		1	1		83%	1,38	R 78,00			R 8,63	11,9	6	R 616,32
	25kg Tunnelguard Thin Spray Skin Liner	25		1	1		83%	1,38	R 143,00			R 7,91	11,9	6	R 564,96
	25kg Superseal Thin Spray Liner Wdl3263	25		1	1		83%	1,38	R 115,00			R 6,36	11,9	6	R 454,34
	Specific Description	Size diameter (m)						Mass of grout	Unit price	Faceplate	Grout cost	Total	Set diameter	Spacing	Cost per metre advance
Steel sets	Becker Ring Set R1Y4000	4							R1872,42			R18 072,42	4	1	R 18 072,42
	Becker Ring Set R1Y3500	3,5							R1749,80			R17 749,80	3,5	1	R 17 749,80
	Becker Ring Set R1Y3000	3							R16559,64			R16 559,64	3	1	R 16 559,64
	Arched Set	3,5							R18072,42			R18 072,42	3,5	1	R 18 072,42
		Length (m)													
I-Beam set	6mx254x146mm Joist I-Sec (Pfc) 31,30kg/M	6							R1 749,27			R 1 749,27	6	1	R 1 749,27
	Prop: Roc: 2.4m To 3.5m:Purple: Rp3520	3,5							R1 498,51			R 1 498,51	3,5	1	R 1 498,51
	1,2m Stromaster 18 Prop 30/Bundle	1,2							R 228,19			R 228,19	1,2	1	R 228,19
	1,4m Stromaster 20 Prop 20/Bundle	1,4							R 257,36			R 257,36	1,4	1	R 257,36
	1,5m Stromaster 18 Prop 30/Bundle	1,5							R 265,55			R 265,55	1,5	1	R 265,55
	1,6m Stromaster 20 Prop 25/Bundle	1,6							R 261,23			R 261,23	1,6	1	R 261,23
	1,8m Stromaster 20 Prop 25/Bundle	1,8							R 281,96			R 281,96	1,8	1	R 281,96
	2,0m Stromaster 20 Prop 20/Bundle	2							R 351,10			R 351,10	2	1	R 351,10
	2,2m Stromaster 20 Prop 20/Bundle	2,2							R 364,64			R 364,64	2,2	1	R 364,64
	2,4m Stromaster 20 Prop 20/Bundle	2,4							R 377,19			R 377,19	2,4	1	R 377,19
Pipe set	6mx80mm Nb Sch40 Ss 316l Seamless Pipe	6		80					R 1 410,00			R 1 410,00	6	1	R 1 410,00
	6mx80mm Nb Sch40 Ss 316l Seamless Pipe	6							R 970,03			R 970,03	6	1	R 970,03
	Galv Pipe 2,3mx100mm Nb T1600/3 Gr Med	2,3							R 650,15			R 650,15	2,3	1	R 650,15

	Galv Pipe 2,3mx150mm Nb T1600/3 Gr Med	2,3							R 914,17			R 914,17	2,3	1	R 914,17
	3.05mx100mm Nb Vict Med Grade Galv Pipe	3,05							R 605,27			R 605,27	3,05	1	R 605,27
		Lagging spacing							Unit cost				Number per row	lagging length (m)	
Lagging	Plate:Fp1001;Foot;5 Mm:Rocprop	1							R 85,98			R 85,98	20	1	R 1 719,60
	750mm Stromaster L/S Headboard								R 58,74			R 58,74	20	0,75	R 1 566,40
	400x400mm Stromaster Headboard 20/Bundle								R 41,10			R 41,10	20	0,4	R 2 055,00
Timber packs		Length m		Timber thickness cm	Pack length m	Pack width m	Tunnel height m	Number of units	Unit price	Pack spacing					Cost per metre advance
	110x9x9cm Timber Composite Pack 132/Bndl	1,1		9	1,5	1,1	2	370	R 28,78	3					R 3 553,68
	150x9x9cm Timber Composite Pack 72/Bndl	1,5		9	1,5	1,1	2	272	R 41,62	3					R 3 768,03
	90mm²X1,1m Composite Pack Support 132/Bn	1,1		9	1,5	1,1	2	370	R 19,30	3					R 2 382,72
	90mm²X1,5m Composite Pack Support 72/Bnd	1,5		9	1,5	1,1	2	272	R 27,77	3					R 2 514,16
Explosives		Hole length m		hole diameter mm	weight of unit kg	Total volume cubic cm	explosive density (g/cm3)	mass of explosive	unit cost	Number of holes	Percentage substance				Cost per metre advance
Bulk explosive	Anfex Explosive (4) 6,25kg Pn 300058	1		25	6,25	490,87	0,8	0,39	R 129,42	20	95%				R 154,50
	Powergel 813 Explosive 25mm 25kg /Case	1		25	25	490,87	0,8	0,39	R 146,02	20	95%				R 43,58
	Danfo Packaged Explosive 25kg Bag	1		25	25	490,87	0,8	0,39	R 128,78	20	95%				R 38,43
	Panex Explosive (1 X 25kg Bag) Pn P0001	1		25	25	490,87	0,8	0,39	R 191,95	20	95%				R 57,29
	Tovex Barrel Explosive 18x585mm Tb18/585	1		25	25	490,87	1,15	0,56	1051,28	20	95%				R 451,02
	Underground Bulk Emulsion Ug100 302191	1		25	1	490,87	1,44	0,71	7,28	20	95%				R 97,77
	Sasol Dds Base Emulsion Pn 16067 Bulk	1		25	1	490,87	1,12	0,55	7,67	20	95%				R 80,12
Sensitizer	Sasol Sds Sensitiser Solution 25l/Drum	1		25	28	490,87	1,12	0,55	191,86	20	5%				R 3,77
	Sasol Dds Sensitiser Emulsion 25l/Drum	1		25	26	490,87	1,03	0,51	191,86	20	5%				R 3,73
		length		Weight	Number of units in a hole	Number of holes	explosive density (g/cm3)	Total units	unit cost						
Cartridges	Conepack Cp3 Explosive 50/Case 9262				1	20	1,15	20	R 22,77						R 455,40
	Conepack Cp10 Explosive 20/Case 9263				1	20	1,15	20	R 83,18						R 1 663,50
	Kubela 420 Explosive 38mmx600mm				1	20	1,15	20	R 5,79						R 115,78
	Kubela 420 Expl 25x200m 210/Case 201132				1	20	1,15	20	R 5,61						R 112,14

Booster	Hornet 12 Booster 12g Units (384/Case)			12g	1	20	1,6	20	3,47						R 69,40
Detonator	Stinger Booster Fuse 15gr 480/Case				1	20		20	R 2,78						R 55,60
	Ied Detonator System 1.8m 100/Case				1	20		20	R 13,94						R 278,80
	Supreme Detonator Assy Ne 2,0m 360/Case				1	20		20	6,4						R 128,00
	Supreme Detonator Assy Ne 2,5m 360/Case				1	20		20	6,75						R 135,00
	Supreme Detonator Assy Ne 3,0m 300/Case				1	20		20	6,9						R 138,00
	Statsafe No 0 Detonator 3.6m Lead 75/Cs				1	20		20	29,7192						R 594,38
	Stopefuse Initiating 4.5mmx1.5m 250/Case				1	20		20	5,14252						R 102,85
	Megadet Lp 4.8m 120lev 240/Case				1	20		20	9,16						R 183,20
CLIP	Possiblast Detonator Positioning Clip								R 1,95						
		length (m)						Total metres per blast							
Detonating cord	Detacord Igniter 3.8g 2x500m Rolls/Case	500					0	100	R2 087,06						R 417,41
	Powercord 10 Det Cord Ael 2x350m Reels	350						100	R2 189,14						R 625,47
	Zapcord Det Cord 10gr/M 2x250m Reel 9256	250						100	R1 567,26						R 626,90
	Zap Cord 2x10gr Rollsx250m Z/Cordbme	250						100	R2 002,63						R 801,05
25/pack	E/Starter Igniter Cord Shurstart 300174	50						100	R 69,89						R 139,78
	Cordtex 10 Det Cord 2x350m Reels 301743	350						100	R1 485,37						R 424,39
					Number of units in a hole	Number of holes		Total units							
Tamping	Dry Clay Tamping Capsule 25mmx170mm				1	20		20	R 27,37						R 547,40
	25mmx240mm Tamping Capsule Aga 247/001				1	20		20	R 20,70						R 414,00
	Tamping Paper Plug Socket 120/Pkt				1	20		20	R 32,46						R 649,20
	Tamping Plug;Polyethylene;500 Per Bag				1	20		20	R 2,00						R 40,00
	Sapling Tamping Pole 20-30mmx6m Ore Pass				1	20		20	R 10,37						R 207,40

Table 9-7: Input interface for case study 1 using engineer spreadsheet

INPUT	Units	Data input	Cost
Damage description			
Line metres	m	32	
Tunnel height	m	3.7	
Tunnel width	m	3.7	
Personnel casualties			**R -**
Hospitalised <14 days	number of cases	0	R -
Hospitatlised >14 days	number of cases	0	R -
Fatalities	number of cases	0	R -
Original support			**R 295 790.74**
Tendons	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	2.1m splitset	R 25 203.20
Straps			R -
Long anchors			R -
Weld mesh			R -
Weld mesh binding spiral			R -
Diamond mesh			R -
Lacing			R -
Shotcrete		40MPA CE40 & OXY FIBRE WETCRETE 30KG BAG	R 36 605.33
Thin spay liner			R -
			R -
Manufacturer sets			R -
Makeshift sets		6MX80MM NB SCH40 SS 316L SEAMLESS PIPE	R 30 080.00
		6MX254X146MM JOIST I-SEC (PFC) 31,30KG/M	R 37 317.76
		PROP: ROC: 2.4M TO 3.5M:PURPLE: RP3520	R 63 936.43
		750MM STROMASTER L/S HEADBOARD	R 50 124.80
Foamcrete		XP500 FOAMCRETE 50X25KG BAGS/BULK BAG	R 52 523.22
Mat Packs			R -
Revenue loss			**R 5 692 500.00**
Number of crews	crews	3	
Average production	t per week	110	
Grade	g/t	10	
Time crew spent standing	in weeks	3	
Price	R/kg	575000	
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial course of action			**R -**
New access	Yes or No	no	
If yes Line metres	m		
Rehabilitation	Yes or No	yes	
If yes, average additional line metres on either side	m	5	
Abandoned	Yes or No	no	
New rehabilitation metres	m	42	
Remedial support			**R 391 246.87**
Tendons	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column	2.1m splitset	R 33 079.20
		2.2m Durabar+Top hat+200mm washer	R 25 164.73
Straps			R -
Long anchors		4.5m Surelock flexible anchor assembly	R 48 656.02
Welded mesh		2.4MX100MMSQ X9.5M LG ROLL MS GALV MESH	R 27 635.03
Binder spiral		1M X 5.6MM GALVANISED WELDED MESH SPIRAL	R 4 046.62
Diamond mesh			R -
Lacing		8 -13MMX30M INTACT LACING ROPE NEW	R 9 632.62
Shotcrete		55XSAV30 N/F WETCRETE 30KG 48/PALLET	R 51 314.38
Thin spay liner			R -
Manufacturer sets			R -
Makeshift sets		PROP: ROC: 2.4M TO 3.5M:PURPLE: RP3520	R 83 916.56
			R -
		PLATE:FP1001;FOOT;5 MM:ROCPROP	R 33 704.16
Geofabric		BAG BULK:30 M;TWILL SP250 2/2;10 M	R 5 160.83
Foamcrete		XP500 FOAMCRETE 50X25KG BAGS/BULK BAG	R 68 936.73
Mat Packs			R -

Table 9-8: Input interface for case study 2 using engineer spreadsheet

	Units	Data input	Cost
Damage			
Line metres	m	5	
Tunnel height	m	3.7	
Tunnel width	m	4.5	
Personnel safety			R 1 914 000.00
Lost Time<14 days	number of injured personnel	1	R 202 000.00
Lost time>14 days	number of injured personnel	1	R 212 000.00
Number of fatalities	number of fatalities	1	R 1 500 000.00
Original support			R 16 528.21
Tendons	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	Mphondo Welded shepherd crook w plate	R 3 324.44
Straps			R -
Long anchors		3.6m M&J 25 ton cable anchor	R 1 746.18
Weld mesh		MESH MS 2.4MX1.3MX5.6MMX100X100MM	R 10 941.13
Weld mesh binding spiral		1M X 5.6MM GALVANISED WELDED MESH SPIRAL	R 516.46
Diamond mesh			R -
Lacing			R -
Shotcrete			R -
Thin spay liner			R -
			R -
Manufacturer sets			R -
			R -
			R -
			R -
Makeshift sets			R -
Foamcrete			R -
Mat Packs			R -
Revenue loss			R -
Number of crews	crews		
Average production	t per week		
Grade	g/t		
Time crew spent standing	in weeks		
Price	R/kg		
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial Action			R -
New access	Yes or No	no	
If yes Line metres	m	0	
Rehabilitation	Yes or No	yes	
If yes, average additional line metres on either side	m	5	
Abandoned	Yes or No	no	
New rehabilitation metres	m	15	
Support system breakdown			R 62 726.99
	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column	2.2m Fish Hook Durabar assembly bolt w washer	R 18 658.56
Tendons			R -
Straps			R -
Long anchors		3.6m M&J 25 ton cable anchor	R 5 616.10
Welded mesh		2.4MX100MMSQ X9.5M LG ROLL MS GALV MESH	R 10 580.98
Binder spiral		1M X 5.6MM GALVANISED WELDED MESH SPIRAL	R 1 549.38
Diamond mesh			R -
Lacing		8 -13MMX30M INTACT LACING ROPE NEW	R 3 688.17
Shotcrete		55XSAV30 N/F WETCRETE 30KG 48/PALLET	R 22 633.80
Thin spay liner			R -
Manufacturer sets			R -
			R -
Makeshift sets			R -
			R -
Foamcrete			R -
Mat Packs			R -

Table 9-9: Input interface for case study 3 using engineer spreadsheet

	Units	Data input	Cost
Damage description			
Line metres	m	41	
Tunnel height	m	3.7	
Tunnel width	m	3.7	
Personnel casualties			**R -**
Hospitalised <14 days	number of cases		R -
Hospitalised >14 days	number of cases		R -
Fatalities	number of cases		R -
Original support			**R 93 227.44**
Tendons	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	2.1m splitset	R 35 520.76
Straps			R -
Long anchors			R -
Weld mesh			R -
Weld mesh binding spiral			R -
Diamond mesh			R -
Lacing			R -
Shotcrete		55XSAV30 N/F WETCRETE 30KG 48/PALLET	R 57 706.68
Thin spay liner			R -
			R -
Manufacturer sets			R -
Makeshift sets			R -
			R -
			R -
			R -
Foamcrete			R -
Mat Packs			R -
Revenue loss			**R 5 692 500.00**
Number of crews	crews	3	
Average production	t per week	110	
Grade	g/t	10	
Time crew spent standing	in weeks	3	
Price	R/kg	575000	
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial course of action			**R 244 656.22**
New access	Yes or No	yes	
If yes Line metres	m	315	
Rehabilitation	Yes or No	no	
If yes, average additional line metres on either side	m	0	
Abandoned	Yes or No	no	
New rehabilitation metres	m	315	
Remedial support			**R 665 235.63**
Tendons	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column	2.2m Fish Hook Durabar assembly bolt w washer	R 365 488.29
			R -
Straps			R -
Long anchors		3.6m M&J 25 ton cable anchor	R 33 002.86
			R -
Welded mesh		2.4MX100MMSQ X9.5M LG ROLL MS GALV MESH	R 207 262.71
			R -
Binder spiral		1M X 5.6MM GALVANISED WELDED MESH SPIRAL	R 25 974.90
Diamond mesh			R -
			R -
Lacing		8 -13MMX30M INTACT LACING ROPE NEW	R 33 506.88
Shotcrete			R -
			R -
Thin spay liner			R -
			R -
Manufacturer sets			R -
Makeshift sets			R -
			R -
			R -
Foamcrete			R -
Mat Packs			R -

Table 9-10: Input interface for case study 4 using engineer spreadsheet

	Units	Data input	Cost
Damage			
Line metres	m	8	
Tunnel height	m	2	
Tunnel width	m	2.8	
Personnel safety			R -
Lost Time<14 days	number of injured personnel	0	R -
Lost time>14 days	number of injured personnel	0	R -
Number of fatalities	number of fatalities	0	R -
Original support			**R 33 927.02**
Tendons	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	2.1m splitset	R 630.08
Straps			R -
Long anchors			R -
Weld mesh			R -
Weld mesh binding spiral			R -
Diamond mesh			R -
Lacing			R -
Shotcrete			R -
Thin spay liner			R -
			R -
Manufacturer sets			R -
Makeshift sets		2,0M STROMASTER 20 PROP 20/BUNDLE	R 2 808.80
		PLATE:FP1001;FOOT;5 MM:ROCPROP	R 343.92
			R -
			R -
Foamcrete			R -
Mat Packs		150X9X9CM TIMBER COMPOSITE PACK 72/BNDL	R 30 144.22
Revenue loss			**R 1 897 500.00**
Number of crews	crews	3	
Average production	t per week	110	
Grade	g/t	10	
Time crew spent standing	in weeks	1	
Price	R/kg	575000	
Is raise line or tunnel accessible?	Yes or No	yes	
If no, remaining tonnes of reef	t		
Remedial Action			R -
New access	Yes or No	no	
If yes Line metres	m	0	
Rehabilitation	Yes or No	no	
If yes, average additional line metres on either side	m	0	
Abandoned	Yes or No	yes	
New rehabilitation metres	m	0	
Support system breakdown			R -
Tendons	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column		R -
Straps			R -
Long anchors			R -
Welded mesh			R -
Binder spiral			R -
Diamond mesh			R -
Lacing			R -
Shotcrete			R -
Thin spay liner			R -
Manufacturer sets			R -
Makeshift sets			R -
			R -
Foamcrete			R -
Mat Packs			R -

9.3 Primary Spreadsheet

Table 9-11: Input interface for case study 1 using primary spreadsheet

	Units	Data input	Cost
Damage description			
Line metres	m	32	
Tunnel height	m	3.7	
Tunnel width	m	3.7	
Personnel casualties			**R 0.00**
Hospitalised <14 days	number of cases	0	R 0.00
Hospitalised >14 days	number of cases	0	R 0.00
Fatalities	number of cases	0	R 0.00
Original support			**R 143 188.19**
	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	Tendons: Rigid	R 47 632.51
		Skin support	R 33 602.00
		Makeshift sets	R 61 953.68
			R 0.00
			R 0.00
			R 0.00
			R 0.00
Revenue loss			**R 5 692 500.00**
Number of crews affected	crews	3	
Average production per crew	t per week	110	
Average ore grade	g/t	10	
Time crew(s) spent standing	in weeks	3	
Gold price	R/kg	575000	
Is raise line or tunnel accessible?	Yes or No	Yes	
If no, remaining tonnes of reef	t		
Remedial course of action			**R 0.00**
New access	Yes or No	No	
If yes, new line metres	m		
Rehabilitation	Yes or No	Yes	
If yes, average additional line metres on either side of damage	m	5	
Abandoned	Yes or No	no	
New rehabilitation metres	m	41	
Remedial support			**R 378 933.48**
	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	Tendons: Rigid	R 36 333.69
		Tendons: Dynamic	R 27 300.57
		Tendons: Long ancho	R 49 334.96
		Areal: Static	R 32 091.49
		Skin support	R 73 892.70
		Makeshift sets	R 159 980.07
			R 0.00
			R 0.00

Table 9-12: Input interface for case study 2 using primary spreadsheet

	Units	Data input	Cost	
Damage				
Line metres	m	5		
Tunnel height	m	3.7		
Tunnel width	m	4.5		
Personnel safety			**R**	**1 914 000.00**
Lost Time<14 days	number of cases	1	R	202 000.00
Lost time>14 days	number of cases	1	R	212 000.00
Number of fatalities	number of cases	1	R	1 500 000.00
Original support			**R**	**17 602.05**
	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	Tendons: Rigid	R	4 009.26
		Tendons: Long ancho	R	1 419.96
		Areal: Static	R	12 172.84
			R	-
			R	-
			R	-
			R	-
			R	-
Revenue loss			**R**	**-**
Number of crews	crews			
Average production	t per week			
Grade	g/t			
Time crew spent standing	in weeks			
Price	R/kg			
Is raise line or tunnel accessible?	Yes or No	Yes		
If no, remaining tonnes of reef	t			
Rehabilitation Course of Action			**R**	**-**
New access	Yes or No	no		
If yes Line metres	m	0		
Rehabilitation	Yes or No	yes		
If yes, average additional line metres on either side	m	5		
Abandoned	Yes or No	no		
New rehabilitation metres	m	15		
Rehabilitation support			**R**	**64 414.33**
	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column	Tendons: Dynamic	R	18 623.65
		Tendons: Long ancho	R	5 172.69
		Areal: Static	R	12 325.74
		Skin support	R	28 292.25
			R	-
			R	-
			R	-
			R	-
			R	-

Table 9-13: Input interface for case study 3 using primary spreadsheet

	Units	Data input	Cost	
Damage description				
Line metres	m	41		
Tunnel height	m	3.7		
Tunnel width	m	3.7		
Personnel casualties			**R**	**-**
Hospitalised <14 days	number of cases	0	R	-
Hospitalised >14 days	number of cases	0	R	-
Fatalities	number of cases	0	R	-
Original support			**R**	**109 479.66**
	Choose damaged support	Tendons: Rigid	R	37 346.31
		Skin support	R	72 133.35
			R	-
			R	-
			R	-
			R	-
			R	-
			R	-
Revenue loss			**R**	**5 692 500.00**
Number of crews affected	crews	3		
Average production per crew	t per week	110		
Average ore grade	g/t	10		
Time crew(s) spent standing	in weeks	3		
Gold price	R/kg	575000		
Is raise line or tunnel accessible?	Yes or No	Yes		
If no, remaining tonnes of reef	t			
Remedial course of action			**R**	**198 669.42**
New access	Yes or No	yes		
If yes, new line metres	m	315		
Rehabilitation	Yes or No	no		
If yes, average additional line metres on either side of damage	m	0		
Abandoned	Yes or No	no		
New rehabilitation metres	m	315		
Remedial support			**R**	**652 409.13**
	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input	Tendons: Dynamic	R	367 817.00
		Tendons: Long ancho	R	32 151.84
		Areal: Static	R	252 440.29
			R	-
			R	-
			R	-
			R	-
			R	-
			R	-

Table 9-14: Input interface for case study 4 using primary spreadsheet

	Units	Data input	Cost
Damage			
Line metres	*m*	*8*	
Tunnel height	*m*	*2*	
Tunnel width	*m*	*2.8*	
Personnel safety			***R 0.00***
Lost Time<14 days	*number of cases*	*0*	*R 0.00*
Lost time>14 days	*number of cases*	*0*	*R 0.00*
Number of fatalities	*number of cases*	*0*	*R 0.00*
Original support			***R 33 099.60***
	Choose support units that were present at the location of rockburst damage from the drop down menu in the data input column	*Tendons: Rigid*	*R 646.69*
		Makeshift sets	*R 3 152.72*
		Timber Support	*R 29 300.19*
			R 0.00
			R 0.00
			R 0.00
			R 0.00
			R 0.00
Revenue loss			***R 1 897 500.00***
Number of crews	*crews*	*3*	
Average production	*t per week*	*110*	
Grade	*g/t*	*10*	
Time crew spent standing	*in weeks*	*1*	
Price	*R/kg*	*575000*	
Is raise line or tunnel accessible?	*Yes or No*	*Yes*	
If no, remaining tonnes of reef	*t*		
Rehabilitation Course of Action			***R 0.00***
New access	*Yes or No*	*no*	
If yes Line metres	*m*	*0*	
Rehabilitation	*Yes or No*	*no*	
If yes, average additional line metres on either side	*m*	*0*	
Abandoned	*Yes or No*	*yes*	
New rehabilitation metres	*m*	*0*	
Rehabilitation support			***R 0.00***
	Choose support units that were used to rehabilitate the location of rockburst damage from the drop down menu in the data input column		*R 0.00*
			R 0.00
			R 0.00
			R 0.00
			R 0.00
			R 0.00
			R 0.00
			R 0.00
			R 0.00